Hydrological performance of green roofs under Mediterranean climate

Native plants in the urban space

Carolina Pinto Brandão

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Orientadores: Professora Doutora Maria do Rosário da Conceição Cameira

Professora Doutora Fernanda Maria dos Reis Torroaes Valente

Júri:

Presidente: Doutora Ana Luísa Brito dos Santos Sousa Soares, Professora Auxiliar do Instituto Superior de Agronomia, Universidade de Lisboa.

Vogais: Doutor Pedro Miguel Ramos Arsénio, Professor Auxiliar do Instituto Superior de Agronomia, Universidade de Lisboa;

Doutora Maria do Rosário da Conceição Cameira, Professora Associada do Instituto Superior de Agronomia, Universidade de Lisboa.

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ABSTRACT

Urban areas generate considerable amounts of storm water runoff due to a high percentage of impervious surfaces. In Mediterranean climates, during winter, there can be large volumes of rainfall in short periods of time causing floods. Green roofs are emerging as a tool for storm water management. The use of native plants, besides promoting biodiversity, reduces maintenance and irrigation requirements, which gains relevance since water is scarce during summer.

This work investigates the influence of rainfall, vegetation and substrate types upon the rainfall-runoff relations under Mediterranean climate. Nine test beds were installed on a building rooftop on the Instituto Superior de Agronomia, incorporating two substrates and five different vegetation covers.

Results for the autumn/winter period show that the vegetated systems did not only reduce the amount of storm water runoff, but also attenuated its peak and delayed its occurrence. Overall mean retention ranged from 63 to 82 %. The combination of shrubs, grasses and mosses proved to be the most effective vegetation cover. Estimations revealed that, by greening the flat roofs of the Municipality of Lisbon, over 224 000 m^3 of water could be retained, relieving the drainage systems and preventing floods.

KEYWORDS: Stormwater management; Green roofs; Mediterranean native plants.

RESUMO

As áreas urbanas geram grandes quantidades de escoamento devido à elevada percentagem de superfícies impermeáveis. No clima mediterrânico, durante o Inverno, podem ocorrer grandes volumes de precipitação em curtos períodos de tempo, causando cheias. As coberturas verdes são uma ferramenta emergente na gestão das águas pluviais. O uso de plantas autóctones, para além de promover a biodiversidade, reduz as necessidades de manutenção e rega, o que toma grande importância visto que a água é um recurso escasso durante o Verão.

O presente trabalho investiga a influência da precipitação, da vegetação e do substrato nas relações precipitação-escoamento, sob clima mediterrânico. Nove tabuleiros experimentais foram instalados na cobertura de um edifício do Instituto Superior de Agronomia, combinando dois tipos de substrato e cinco coberturas vegetais.

Os resultados referentes ao período de Outono/Inverno mostram que os sistemas contendo vegetação reduziram a quantidade, atrasaram o início e atenuaram o pico do escoamento. A retenção média variou entre 63 e 82%. A combinação de arbustos, gramíneas e musgos foi a cobertura vegetal com melhor desempenho. Estimativas revelaram que, se todas as coberturas planas de Lisboa fossem convertidas em coberturas verdes, reter-se-iam mais de 224000 m^3 de água, aliviando os sistemas de drenagem e prevenindo cheias.

PALAVRAS-CHAVE: Gestão de águas pluviais; Coberturas verdes; Plantas autóctones mediterrânicas.

RESUMO ALARGADO

No decurso da História, os jardins em terraços e no topo de edifícios têm sido construídos principalmente com objectivos estéticos e de lazer, proporcionando espaços verdes de recreio e contemplação. Nos anos setenta do século XX, o desenvolvimento tecnológico e científico e a generalização do betão como material de construção permitiram uma implementação mais alargada das coberturas verdes. As investigações relativas aos benefícios ambientais, sociais, ecológicos e, consequentemente, económicos que estas estruturas poderiam trazer para o espaço urbanos e para os seus habitantes, tanto à escala do edifício como da cidade, levaram a que a sua instalação se passasse a fazer de um ponto de vista mais ecológico.

O aumento constante da população urbana, da área das grandes cidades e da impermeabilização do solo tem originado inúmeros problemas ambientais e ecológicos, criando novos desafios de gestão, nomeadamente ao nível das águas pluviais, que passam a escoar à superfície ou nos sistemas de drenagem artificiais. Devido à escassez de superfícies de infiltração e retenção, a água da precipitação entra nos sistemas de drenagem em grandes quantidades, ultrapassando a sua capacidade e causando, muitas vezes, cheias de grande impacto que degradam o espaço urbano e põem em risco pessoas e bens. As alterações climáticas representam uma agravante para estas situações uma vez que levam ao aumento da ocorrência de eventos de precipitação de grande duração e intensidade. Nos últimos tempos, tem-se assistido a um aumento da consciência da necessidade de tomar medidas que possam conduzir à atenuação desses problemas, tendo por base princípios ecológicos e de conservação da natureza.

Em muitos os países, estados e cidades a construção de coberturas verdes é promovida através de instrumentos legais de natureza variada. A isenção de impostos e taxas é das práticas mais comuns mas, em alguns casos, a instalação da cobertura verde é obrigatória em novos empreendimentos.

É possível encontrar, entre a literatura disponível, estudos em que foi testada a capacidade de uma cobertura verde para reter a água da precipitação e atrasar o início do escoamento. Os estudos variam em localização, composição e profundidade do substrato, tipo de vegetação e inclinação da cobertura. As espécies vegetais geralmente utilizadas são as do género *Sedum*, muitas vezes em monoculturas, pela sua resistência à seca, insolação, calor e tolerância a substratos pouco profundos, permitindo a redução dos cuidados de manutenção e da carga da cobertura. No entanto, o seu uso generalizado limita a função da cobertura verde enquanto promotora de biodiversidade.

Mais recentemente foram publicados estudos em que foram testadas plantas de outras espécies e tipos fisionómicos, comparando o seu desempenho com o de plantas do género *Sedum*. As plantas testadas (outras suculentas, herbáceas ou arbustos) têm mostrado capacidade de igualar ou superar a *performance* do *Sedum* sp., trazendo vantagens ao nível da biodiversidade, uma vez que, se forem autóctones, estão integradas nas condições locais

A bibliografia disponível é escassa em estudos desenvolvidos em clima mediterrânico e com recurso a espécies vegetais autóctones, não existindo estudos relativos a Portugal.

O presente trabalho tem como objectivo principal avaliar a capacidade de diferentes combinações de substrato e vegetação para reter a água da precipitação e atrasar o respectivo escoamento, assim como avaliar o impacto potencial que a instalação de coberturas verdes nos edifícios coberturas planas, existentes no Município de Lisboa, poderá ter na gestão das águas pluviais.

Foi instalado um dispositivo experimental na cobertura do edifício do Herbário *João de Carvalho e Vasconcellos*, do Instituto Superior de Agronomia. Foram colocados nove tabuleiros de simulação de coberturas verdes, oito deles combinando dois tipos de substrato (S1 e S2) com cinco coberturas vegetais diferentes (*Rosmarinus officinalis* L., *Lavandula stoechas* subsp. *luisieri* L., *Brachypodium phoenicoides* (L.) Roem. & Schulz., musgos e combinações entre si) e um apenas com substrato. A camada de substrato foi colocada sobre um sistema de cobertura verde comercial, composto por uma manta não tecida filtrante, uma camada de drenagem e uma manta não tecida para retenção de água e protecção.

Entre Setembro de 2014 e Fevereiro de 2015, foram medidos a precipitação, o escoamento e o teor de água no substrato. Analisaram-se os dados obtidos com base na identificação de eventos de precipitação independentes e agruparam-se esses eventos de acordo com a sua intensidade máxima e duração, criando-se classes relativamente homogéneas, de modo a facilitar a identificação dos vários factores que determinam a caracterização do escoamento. De seguida, definiram-se quatro variáveis para caracterizar as relações entre a precipitação e o escoamento: retenção da precipitação, atraso no início do escoamento, atenuação do pico de precipitação e atraso do pico de escoamento. A primeira análise focou o efeito das chuvadas de diferentes classes na resposta do escoamento. Depois, cada tratamento foi analisado e comparado com os restantes, sem se descriminarem classes de precipitação.

Globalmente, a retenção média foi 71,43 %, o atraso médio do início do escoamento foi 1,96 h, a atenuação média do pico foi 90,59 % e o atraso médio do pico foi 1,60 h .

Concluiu-se que as diferentes classes de precipitação tiveram impacto na resposta do escoamento, principalmente nas classes mais extremas. Em chuvadas curtas e de baixa intensidade, a resposta dos tratamentos foi pouco diferenciada, sendo as percentagens de retenção sempre elevadas. Por outro lado, em chuvadas longas de grande intensidade a capacidade de retenção foi reduzida em todos os tratamentos. Muitas vezes, em classes intermédias, a eficiência dos tratamentos piorou com o aumento da duração da chuvada, para uma mesma classe de intensidade.

O tabuleiro contendo substrato do tipo um e uma mistura de todas as espécies vegetais utilizadas foi frequentemente aquele que demonstrou melhor desempenho. O substrato um mostrou ter maior capacidade para reter água que o substrato dois. De um modo geral, o desempenho dos tratamentos foi melhor quanto mais complexa era a sua cobertura vegetal (mistura de plantas - arbustos - gramíneas - musgos), tendo o tabuleiro sem vegetação apresentado quase sempre os piores resultados.

A melhor combinação de substrato e vegetação foi utilizada como base para a estimativa do impacto que uma aplicação generalizada de coberturas verdes (nos edifícios com coberturas planas existentes no Município de Lisboa) teria na gestão das águas pluviais. Leandro (2011), na sua tese de mestrado identificou e quantificou as coberturas planas existentes no município, com recurso a uma metodologia baseada em software SIG. Os dados obtidos por esse autor foram combinados com a retenção obtida, no presente estudo, para uma chuvada que havia causado cheias no município, e o resultado revelou que seria possível reter mais de 224 000 m^3 de água num evento deste tipo. O valor obtido foi, ainda, comparado com a capacidade de vários reservatórios subterrâneos propostos no Plano Geral de Drenagem de Lisboa, tendo-se verificado, com base na metodologia adoptada, que este volume de retenção teria um impacto real na diminuição das cheias na cidade.

Concluiu-se que, ainda que as características particulares do clima mediterrânico possam apresentar alguns desafios, as coberturas verdes podem constituir uma ferramenta útil e eficaz, se integradas na gestão das águas pluviais em espaço urbano. Verificou-se também que o recurso a plantas autóctones não apresenta desvantagens, em termos do cumprimento das funções hidrológicas da cobertura, relativamente às mais frequentemente utilizadas, do género *Sedum*, trazendo ainda benefícios relativos à biodiversidade e um potencial estético superior.

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Symbol	Physical variable	Dimensions	SI Units
A_B	Area of the test bed	L^2	m^2
A_{PD}	Average peak delay	T	h
A_{RD}	Average runoff delay	T	h
A_{RG}	Area of the rain gauge	L^2	m^2
C_{TB}	Capacity of the tipping bucket	L	mm
D	Duration	T	h
d_{RF}	Total rainfall depth	L	mm
d_{RO}	Total runoff depth	L	mm
D_S	Substrate depth	L	cm
F_C	Calibration factor	dim	
I_{10}	Maximum intensity in 10 minutes	LT^{-1}	mm h^{-1}
I_{RF}	Maximum rainfall intensity in 10 minutes	LT^{-1}	mm h^{-1}
I_{RFa}	Average rainfall intensity	LT^{-1}	mm h^{-1}
I_{RO}	Maximum runoff intensity in 10 minutes	LT^{-1}	mm h^{-1}
I_{ROa}	Average runoff intensity	LT^{-1}	mm h^{-1}
N_R	Number of rainfall events that produced runoff	dim	
PA	Peak Attenuation	dim	%
PD	Peak delay	T	h
PD_i	Peak delay index	dim	
R	Rainfall retention	dim	%
R_2	Runoff	LT^{-1}	mm / 2 min
RD	Runoff delay	T	h
TP_{RF}	Time of rainfall peak	T	h
TP_{RO}	Time of runoff peak	T	h
T_{RF}	Time of rainfall start	T	h
T_{RO}	Time of runoff start	T	h
VDL	Value from data logger	T^{-1}	tips / 2 min
WS	Water storage in the substrate	L	mm
WS_{max}	Maximum amount of water that can be stored in the test bed	L	mm
WS_R	Relative water storage	dim	%
θ	Water content of the substrate	dim	$cm^3\ cm^{-3}$
θ_{FC}	Water content at field capacity	dim	$cm^3\ cm^{-3}$
θ_S	Water content of the substrate at saturation	L	mm
θ_{WP}	Water content at permanent wilting point	dim	$cm^3\ cm^{-3}$

1. INTRODUCTION

A green roof is any vegetated area constructed on top of a building or over a built underground structure. Throughout time, green roofs have been constructed mainly on an aesthetics perspective, as an embellishment. Since the 1970s, with the technological and scientific development and the generalization of concrete constructions, their implementation has spread, as the buildings were able to support a higher load (Grant *et al.* 2003; Earth Pledge Foundation 2005). Germany was where the multiple benefits of green roofs have first been studied, from the building to the city scale, leading to the construction of vegetated rooftops under a more ecological purpose (Getter and Rowe 2006).

Today, it is known that green roofs may impact the urban inhabitants and the urban environment in many ways. These structures provide a wide range of benefits: reduction of the heat island effect, rainfall water harvesting, rainfall water retention, keeping it from entering the drainage systems, increase of biodiversity, maintenance of the building's inside temperature, increase of the lifetime of the roof membrane and they may also provide green recreational spaces in densely urbanised spaces, where the ground is no longer available (Önder 2014; Grant *et al.* 2003; GRO 2014).

As the urban population and the impervious urban surface keep growing, there has been a higher concern in promoting measures that may lead to a bigger balance between nature and the urban space.

Storm water management is one of the challenges that city managers and planners have faced over the past years. Rainwater enters the drainage systems in large amounts due to the lack of infiltration and to high intensity rainfall events concentrated in time, causing overflows and floods (USEPA 2003). Under a Mediterranean climate, in which the rainfall is concentrated on the winter season, this phenomenon is intensified.

In many countries, states and cities, policy instruments promote the construction of green roofs by reducing fees and taxes to the builders and land owners who choose to integrate them in their building developments, or even by making it mandatory in new developments.

Many studies have tested the green roofs capacity to retain and delay the rainfall water by combining different types of substrates and vegetation, under different climates. The results have always pointed that these structures, when implemented in large scale, may in fact have a significant impact on the urban storm water management.

The species most commonly used as vegetation cover on green roofs is *Sedum* sp., mostly because of its high resistance to draught, insolation and heat and its adaptation to shallow substrates, allowing for low maintenance and lighter systems (Dvorak and Volder 2010). The widespread use of this type of vegetation, many times in monocultures, limits the green roofs' function as a promoter of biodiversity (Dunnett *et al.* 2008).

Studies testing the effectiveness of plants of other species and physiognomical types have shown that these, most of the times, equal or exceed the *Sedum* sp. performance in providing the ecological services expected from a green roof (Lundholm *et al.* 2010; MacIvor and Lundholm 2011).

The available literature is poor in studies taken under Mediterranean climate using native species and, specifically for Portugal, these studies are inexistent.

The present study was developed as part of the project NativeScapeGR (FCT Project Expl/atp-arp/0252/2013) and had the general objective of analysing the hydrological performance of a green roof under Mediterranean climate, using portuguese native plants. In particular, it was intended to:

- analyse the influence of different rainfall patterns in the runoff response;
- assess the performance of different substrates;
- assess the performance of different vegetation covers (shrubs, grasses, moss) and understand if they present any (dis)advantage compared to most commonly used plant species;
- estimate the potential impact on storm water management of the wide scale implementation of green roofs in the Municipality of Lisbon.

This work was divided in 6 chapters. Chapter 2, the literature review, intends to gather and synthetize information for the contextualization of the topics debated along the following chapter. Chapter 3 describes the materials and methods used in the experiment, from the assembly of the experimental set up to the analysis of the collected data. Chapter 4, describes, analyses and discusses the data, comparing it to the results obtained by other authors. In chapter 5 is made an application of the results to the Municipality of Lisbon. Finally, chapter 6 presents the main conclusions drawn from the whole work.

The experiment has been set in the flat rooftop of one of the buildings of the Instituto Superior de Agronomia, University of Lisbon, Portugal. The experimental set up consisted of nine test beds, eight combining two types of substrate and five different native vegetation covers and one with substrate only, resulting in six different treatments.

The measurements of rainfall, runoff and water storage in the substrate were performed through most of the wet season, from September 2014 to February 2015. The obtained data was then treated, based on the identification of independent rainfall events. At first, rainfall, runoff and soil moisture were analysed as a hole, without individualizing the test beds. The rainfall events were grouped according to their maximum rainfall intensity and rainfall duration. The creation of more homogeneous classes should help to understand how the many factors influencing the runoff response acted, as well as allow for a more accurate statistical analysis.

Four variables where selected to characterize the rainfall-runoff relations: storm water retention, runoff delay, peak attenuation and peak delay. The first analysis focused on understanding how different rainfall events (differing in maximum intensity and duration classes) dictated the runoff response within each green roof treatment. After, each treatment's response was analysed without discriminating rainfall classes and was compared to the other treatments.

After the best performing combination of substrate and vegetation was identified, it was used as an example to estimate the impact that the greening of the flat roofs of the municipality of Lisbon would have on the storm water management. Leandro (2011), in his master thesis, had already identified and quantified the flat roof area of the municipality using GIS software. The results obtained in the presented study were applied to the ones reported by Leandro (2011), resulting in an estimation of the rainfall retention capacity of green roofs, if they were implemented in the reported flat roof area. Then, to understand the impact of the potential green roofs area, it was compared to the built area of the municipality (by excluding the green infrastructure) and the obtained volume of retained rainfall was compared to the volume of the underground reservoirs proposed in the Drainage Master Plan developed by the municipality (Leboeuf *et al.* 2015).

2. LITERATURE REVIEW

Through this chapter it is intended to provide information that may sustain the main idea behind the study here developed: that green roofs may have a role in urban storm water management, under Mediterranean climate. The first section of this chapter provides background information pertaining to urban storm water management and flood mitigation. The second section introduces green roofs as a best management practice for storm water management, presenting an introduction to the green roofs' history, design and function, and general benefits of their implementation. Section 2.3 refers to the existing legislation regarding the implementation of green roofs worldwide, including the Portuguese case. The following section introduces the focus of this work, which is the hydrological performance of green roofs. The last section debates the use of green roofs in the Mediterranean climate, emphasizing the importance of using native species as vegetation cover.

2.1 Urban storm water management

2.1.1 Urban water management in the 21st Century

Since 1950 and according to the United Nations (2014), the world's urban population has grown from 746 million to 3.9 billion and Europe represents 14 % of that value. The number of cities with more than 10 million inhabitants, worldwide, has almost tripled since 1990, going from 10 to 28 (United Nations 2014). It is also predicted that the proportion of urban population will keep increasing, mainly in developing countries. This exponential growth requires appropriate development of urban planning and management approaches regarding water and sanitation, energy, transportation, information, communications, services, equality of opportunities and nature (United Nations 2014).

The growth of urban areas is associated to the increase of impervious areas, which leads to the generation of more storm water runoff. Most of the rainfall is not allowed to infiltrate into the ground and runs off at higher speed and quantity than it would happen in natural or rural areas. According to the United States Environmental Protection Agency (2003), a typical city block generates more than five times more runoff than a woodland area of the same size (Figure 2.1). The decrease in infiltration may cause problems concerning groundwater quality and water availability, among others. Thus, urban development should be designed and built in order to minimize runoff increases (USEPA 2003).

To face this problem many countries and cities have adopted management guidelines based on sustainability principles. In English-speaking countries (UK, USA, Australia) those programs are called LID (Low Impact Development), SUDS (Sustainable Urban Drainage Systems), WSUD (Water Sensitive Urban Design) or BMP (Best Management Practices).

These are storm water management tools to be applied as close as possible to the source. Such techniques aim to conserve natural areas, reduce development impacts and reduce runoff rates by maximizing surface roughness, infiltration opportunities, flow paths, evapotranspiration, groundwater recharge and re-use of storm water through techniques like rain barrels, storage tanks, biofiltration swales, pervious pavement, green roofs, rain gardens (USEPA 2003; Roy *et al.* 2008, Stovin *et al.* 2011; Gedge and Newton 2008).

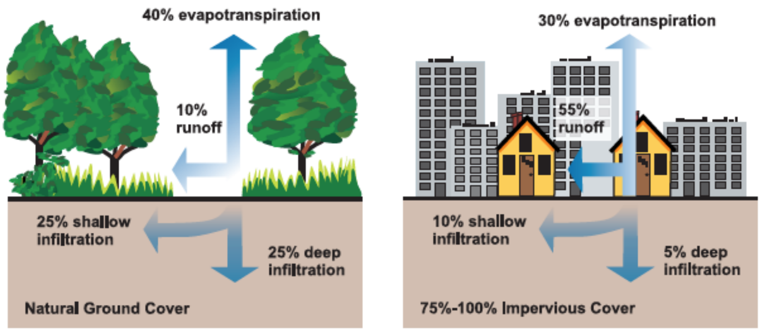


Figure 2.1 – Influence of the ground cover upon runoff generation (USEPA 2003).

These techniques are meant to be used in a chain system, providing better storm water management than any single element alone (Stovin 2010). The ultimate goal of these strategies is to reproduce the original natural hydrologic functions of the site (Palla *et al.* 2010; Voyde *et al.* 2010).

The capture of water close to the source of runoff may reduce flood frequency and infrastructure damage (Roy *et al.* 2008). It may also increase the recharge of local ground water resources and streams, reduce stream erosion, favor the development of biodiversity and improve water quality (Palla *et al.* 2010).

All the mentioned strategies contribute to the reduction of the volume of runoff entering the underground sewerage system and of its required storage capacity, decreasing costs related to the size of the pipe network and decreasing overflow episodes (Gedge and Newton 2008).

2.1.2 Storm water management in the city of Lisbon

Urban growth may lead to the canalization of the water lines with the streambeds being replaced by streets, buildings, etc. This phenomenon has occurred in Lisbon since the Roman Period and was accentuated after the earthquake of 1755. Despite the artificiality of the urban space, the physiognomy of the territory is still determinant to the storm water drainage when large storms hit the city (Soares *et al.* 2005).

The Municipality of Lisbon has faced yearly flood episodes due to the overload of it's sewerage and drainage systems. In 2014, the two most memorable episodes occurred on September 22nd and on the afternoon of October 13th, when a 34 mm rainfall with a duration of 60 minutes (20 years return period) hit the city (Expresso 2014). In both cases the storm resulted in floods in several important points of the city, preventing circulation (Figure 2.2), leading to the closure of subway stations and tunnels and causing countless material damages (Público 2015).

Lisbon suffers from an aged drainage network, which receives water from the surrounding municipalities. The sewerage system is a mix of the separate and the combined types, meaning that some network sections transport a mix of storm water runoff and domestic and industrial sewage. Furthermore, the tides of the Tagus River interfere with the system hydraulic performance (Saldanha Matos *et al.* 2006). The coincidence of large and intense rainfall events with the high tide has many times lead to the flooding of the riverfront and other upstream areas (Assembleia Municipal de Lisboa 2015), as happened in the events previously referred. Figure 2.3 shows, in blue, the areas that are in risk of flooding in the Municipality of Lisbon, with the darker blue representing the areas with very high vulnerability. According to Oliveira (2005), nowadays, the floods tend to occur in areas of lower altitude and slope, located in valley bottoms and over old natural drainage lines, which receive and accumulate water.

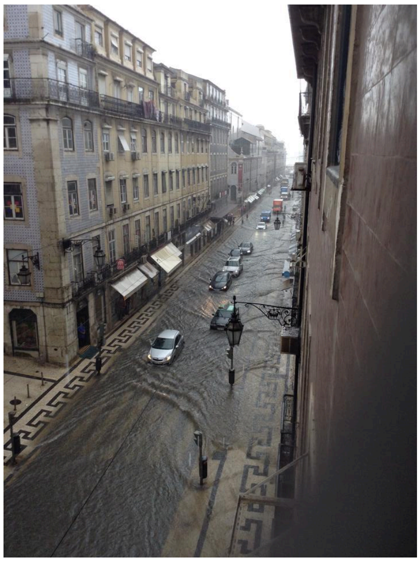


Figure 2.2 – Prata Street in 09/22/2014 (Photo by Ercília Sousa).

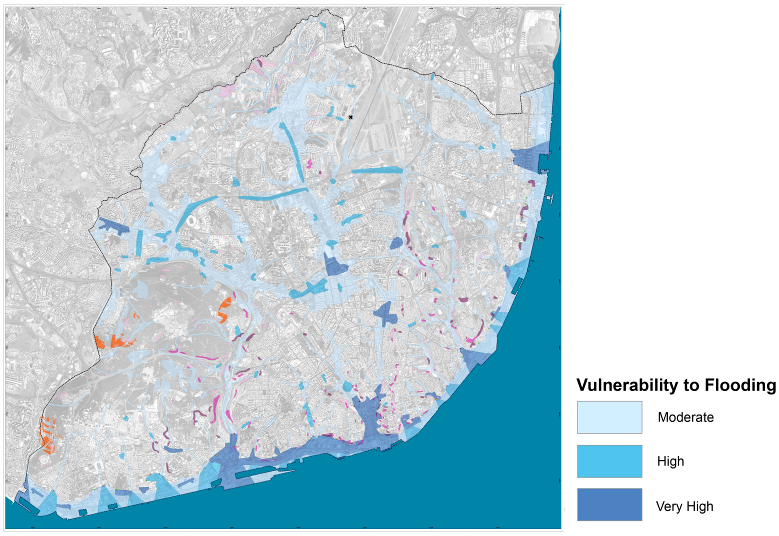


Figure 2.3 – Plan of natural and anthropic risks (adapted from CML 2012).

The referred limitations of Lisbon's sewage system result in floods, entering of seawater into the system and direct discharge, in the water bodies, of untreated wastewater, due to the lack of storage and treatment capacity. Estimations of the maximum flow entering the treatment stations were made in the year of 2001 by Saldanha Matos *et al.* 2006. The maximum flow in dry weather was approximately 4300 L s^{-1}, while for wet weather it reached 340000 L s^{-1} (almost 80 times higher) for events with 2 years return period and 680000 L s^{-1} (almost 160 times higher) for events with 50 years return period. As the events that caused floods in 2014 had a 20 years return period, it appears that the drainage system was loaded with amounts of water between those two values.

The current Drainage Master Plan of Lisbon (in force since 2006) intends to (Saldanha Matos *et al.* 2006): treat all the domestic and industrial wastewaters; implement combined sewer systems (when possible); adopt source control measures (taking advantage of the capacity of infiltration and storage of permeable areas); create rain water reservoirs in strategic locations and implement real time infra-structure management by installing a monitoring network .

More recently, in June 2015, the Municipality of Lisbon announced a new Drainage Master Plan, which focus on transporting separately, through two pipes of large dimensions, the excess storm water, directly into the Tagus River (CML 2015c). The plan takes in consideration the previously proposed reservoirs for the areas more subjected to floods. For the watershed of Alcântara, the construction of five reservoirs is planned, totalizing a capacity of 170 000 m^3 (approximately 54 olympic swimming pools) (Leboeuf *et al.* 2015).

2.2 Green Roofs

Although roof gardens have been part of history throughout many periods, their expansion only occurred in the 1970s, as a consequence of the technological development and growing environmental concerns, in countries like Germany, Switzerland, the USA and in Scandinavian countries (Whalley 1978, cited by Grant *et al.* 2003; Earth Pledge Foundation 2005).

Nowadays, commercial green roofs are composed by layers that may vary in materials and configuration, but that usually share the same function among manufacturers (Figure 2.4). From bottom to top the layers are: waterproof membrane (keeps moisture from entering the building), root barrier (protects the roof membrane from root damage), drainage layer (allows water to flow away and many times has an egg box shape, providing some water storage for plant use), filter fabric layer (keeps thin substrate particles from clogging the drainage layer) and, at last, substrate and vegetation layers (Getter and Rowe 2006, Berndtsson 2010, Fioretti *et al.* 2010).

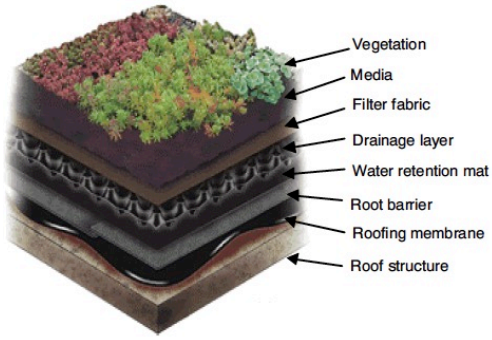


Figure 2.4 - Green roof component layers (Hathaway *et al.* 2008).

It is estimated that 14 % of all flat roofs in Germany are green (Earth Pledge Foundation 2005) and this country became a reference in the green roof industry. According to "The Guidelines for the Planning, Execution and Upkeep of Green Roof Sites", first published by The German Landscape Development and Landscaping Research Society in 1982 (Oberndorfer *et al.* 2007), there are three types of roof greening:

- intensive greening, which includes the planting of shrubs, coppices, lawn areas and even trees, with high water and maintenance demands, using substrate depths from 15 to 200 cm, that can be compared, in terms of use, to parks and green areas at ground level;
- simple intensive greening, which is characterized by the use of grass, shrubs and coppices, but with less water and nutrient needs when compared to the previous type, using substrate depths from 12 to 100 cm;
- extensive greening, the less expensive and with lower water and maintenance requirements type, which is usually vegetated with plants very well adapted to the conditions of the site (e.g. mosses, succulents, herbaceous plants and grasses) that require substrate depths from 4 to 20 cm (FLL 2002).

There is a disagreement between authors in what refers to the classification of green roofs as extensive or intensive. For Grant *et al.* (2003), the substrate depth of an extensive green roof may range from 5 to 20 cm, depending on the vegetation cover, which may vary between mosses, succulents, grasses and wildflowers. The classification described by Getter and Rowe (2006) is based on criteria related with maintenance requirements. They consider that intense green roofs aim to replicate the landscape of ground level, therefore using shrubs and trees and substrates usually deeper than 15 cm, while extensive green roofs require minimum maintenance, have shallower depth and the plantations are limited to herbs, grasses, mosses and succulents. Hathaway *et al.* (2008) consider that in extensive green roofs, the vegetation, which can include mosses and succulents, should retain large amounts of water (showing a concern with the performance of the green roof), its substrate depth should vary from 5 to 150 cm and it shouldn't require high maintenance. For this author, intensive green roofs have a deeper substrate layer, due to the characteristics of the vegetation, and require irrigation. The authors of London's technical report on green roofs and walls (Gedge and Newton 2008) add that extensive green roofs generally provide biodiversity opportunities, due to not being disturbed by humans and due to the presence of native vegetation (planted or naturally colonized). On the other hand, the usually thinner substrate layer that characterizes extensive green roofs is lighter than in intensive green roofs, making them more suitable to the retrofitting on existing buildings. Most authors seem to agree that intensive green roofs require more maintenance, have deeper substrate layers, can support larger plants and are many times intended for recreational use. Extensive green roofs are cheaper to maintain, suitable for retrofitting of existing buildings and their aim is mainly to provide thermal, hydrological and/or biodiversity benefits (Palla *et al.* 2010; Berndtsson 2010; Önder 2014; GRO 2014). Probably the boundaries between the two situations are not well defined, depending many times on site and climate conditions. Pevzner (2014) suggests that green roofs of the extensive type are ideal for governmental policy applications due to their shallower substrate, since the building must be structurally strong enough to support the added weight of the green roof. Concerning the vegetation, deeper substrates have higher water holding capacity and offer winter protection against root freezing (Getter and Rowe 2006).

According to Getter and Rowe (2006), the green roof substrate must be light weight, well drained, have good water and nutrient holding capacity and structural durability. The composition of the substrates used in green roof experiments and studies is very diverse. Some of the more common are sandy loam, sand, expanded clay, expanded slate, pumice, zeolite, scoria, perlite, crushed brick, vegetable compost, digested fibber and peat (Hutchinson *et al.* 2003; VanWoert *et al.* 2005, Hathaway *et al.* 2008, Berghage *et al.* 2009; Fioretti *et al.* 2010; Lundholm *et al.* 2010; Palla *et al.* 2010; Stovin 2010; Voyde *et al.* 2010; Stovin *et al.* 2011; Beecham *et al.* 2012; Fassman-Beck *et al.* 2013; Razzaghmanesh and Beecham 2014).

Regarding the vegetation, most of the types of commercialized extensive green roofs have a uniform *Sedum* sp. coverage. This type of succulent plant survives in the extreme environmental conditions of the roof – shallow substrate, wind, sun exposure, no irrigation. They have shallow root systems and the ability to use water very efficiently (Dvorak and Volder 2010). In spite of the widespread use of this type of vegetation, *Sedum* sp. mats may have reduced biodiversity values when compared to other vegetation types because of their limited flowering period and structural diversity (Dunnett *et al.* 2008). Oberndorfer *et al.* (2007) considers that almost any plant can be used for green roof application, as long as it is suited to the climatic region, grows in appropriate substrate and its water needs are satisfied.

Some studies have analysed different plant species and life-form groups and their performance on green roofs. Lundholm *et al.* (2010) concluded that the combination of plants of different physiognomies resulted in the best performance results, when compared to monocultures. In the study of MacIvor and Lundholm (2011), some of the native species showed better performance than the common green roof *Sedum* sp. and grass species tested in Lundholm *et al.* (2010). Anderson *et al.* (2010) studied the potential of mosses for use on green roofs and concluded that they can significantly contribute to stormwater management, due their lack of roots and high tolerance to drought. In their study, mosses surpassed vascular plants in the water retention results.

Green roofs have proven to contribute with many benefits to the urban space. Depending on the type of green roof, its benefits may be (Önder 2014; Grant *et al.* 2003; GRO 2014):

- environmental – attenuation storm water runoff and peak flow, improvement of runoff water quality, reduction of the urban heat island effect, noise reduction, electromagnetic radiation reduction;
- ecological – increase of biodiversity, complement of the urban green infrastructure;
- economical – energy efficiency, increase of roofing membrane durability, urban agriculture, increase of real estate value;
- other public benefits – aesthetic improvement, improved health and well being, educational opportunities.

Ernst and Weigerding, were, in 1985 (cited by Getter and Rowe 2006), the first to mention the water retaining capacity of green roofs in the German literature. Since then, there have been many authors who have studied the capacity of these structures to hold the rainfall water and delay its entry into the sewer systems. Many consider storm water runoff mitigation to be one of the most important benefits of green roofs to the urban space. Contrary to what happens on impervious surfaces, the water falling onto a green roof will be held in the pore space of the substrate, stored in the drainage layer, used by plants and sent back to the atmosphere by evapotranspiration (Figure 2.5). Therefore, the storm water that runs off from a green roof goes through a much longer path until it reaches the usually overloaded drainage systems (GRO 2014).

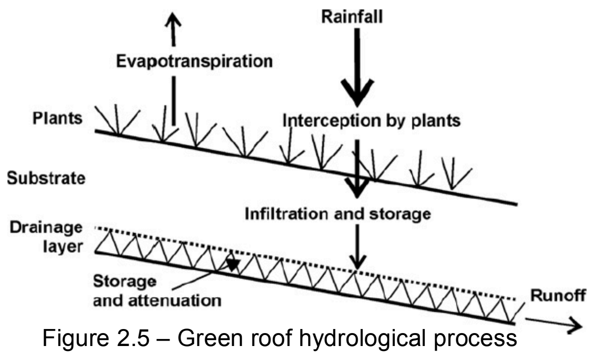


Figure 2.5 – Green roof hydrological process (Stovin *et al.* 2012).

Green roofs have the potential to achieve the goals of water quantity, quality and amenity, referred in the previous sections, and, contrary to most of the other techniques of BMP, SUDS, WSUD or LID, do not require additional ground area beyond the building, which can be an advantage in many cases, considering the density of the urban space (Stovin 2010, Razzaghmanesh and Beecham 2014, Berghage *et al.* 2009).

2.3 Policies for the implementation of green roofs

2.3.1 Around the world

Many cities and countries have already recognized the potential of green roofs as a tool to reduce some of the consequences of the exponential urban development. These territories have implemented policies to promote the construction of green roofs, with German being the best example (it is estimated that 14 % of all flat roofs are green) where various instruments have been successfully applied for more than 30 years (Wolfgang and Roland 2011).

These policy instruments can be implemented at country, state or municipal level or even on restricted, pilot study, areas. Despite the legal differences, some of these incentives are transversal to most of the countries that have already set the example on the valorization of green roofs, and consist in (Wolfgang and Roland 2011; Gedge and Newton 2008):

- Financial subsidies;
- Reduced storm water fees (recognizing that green roofs are in fact able to retain some of the rainfall water, contributing to the reduction of the total volume of water being conveyed into the drainage systems);
- Regulation in land-use plans (green roofs may be mandatory in new developments);
- Ecological compensation (the ecological compensation is actually in the roof of the constructed building, instead of in a distant site which may not be ecologically related to the construction site);
- Density bonus (by including a green roof in the project, the constructor may be allowed to exceed the gross floor area or number of storeys usually permitted);

Besides these direct and indirect incentives, public information is a key driver in the awareness of private and public investors and decision makers for the benefits of the installation of green roofs. In some cases, the greening of public buildings by the municipalities has resulted as an example, followed by private entities.

Table 2.1 summarizes some of the currently existing green roof policies around the world, describing the specific implementation of the previously referred measures in countries and cities with different legislation and history. A more complete Table is presented in Appendix I.

Since 1989, with the implementation of the subsidies program in the city of Linz, Austria, until the end of 2001, 237 projects received green roof subsidies (4.77 million €), resulting into about 268000 m^2 of green roofs. In 2001 and 2002, 740000 € were made available for the development of 47000 m^2 of green roofs (Linz 2002 cited by Ngan 2004).

Table 2.1 – Selected green roof policies by country, state or city

Country / State / City	Policies
Austria – Linz	• A subsidies program started in 1989; • Linz Green Space Plan 2001 - New and proposed buildings with an area of over 100 m^2 and a slope of up to 20º are to be greened. The growing medium shall have a thickness of at least 12 cm and the coverage of living plant material shall be at least 80%; • The roof surfaces of underground structures are to be greened. The growing medium shall have a thickness of at least 50 cm and the coverage of living plant material shall be at least 80%; • Up to 30% of eligible costs are reimbursable (Ngan 2004).
Canada – Toronto	• First City in North America to have a bylaw to require and govern the construction of green roofs on new development, adopted by Toronto City Council in May 2009, requiring green roofs on new commercial, institutional, industrial and residential development with a minimum Gross Floor Area of 2000m^2 (City of Toronto website 2015).
Denmark – Copenhagen	• All new roofs with a slope under 30° are to be landscaped (Wolfgang and Roland 2011).
Germany	• Reductions in storm water fees of up to 80% for buildings with green roofs in 13 cities (Peck 2002); • 43% of cities offer financial incentives for roof greening (Grant *et al.* 2003); • 17% of cities offer reduced sewage disposal charges for developments with green roofs (Grant *et al.* 2003).
Germany – Berlin	• The city has pioneered the 'biotope area factor' (BAF); • Green roofs result in a reduction of drainage charges of 50% whether they are connected to the storm drains or not (Ngan 2004).
Japan – Tokyo	• New private buildings with a gross floor area larger than 1000 m^2, and new public buildings with a gross floor area greater than 250 m^2, must have green roofs in 20 % of their roof areas or the owners face an annual fine; • The Japanese government is now applying Tokyo's policy nationally (Grant *et al.* 2006 cited by Gedge and Newton 2008).
Switzerland – Basel	• Extensive green roofs have to be constructed on all new buildings with flat roofs (Brenneisen 2002); • The design and use of substrates for extensive green roofs are part of the city's current biodiversity strategy; • On roofs of over 500 m^2 the substrates must be composed of appropriate natural soils from the surrounding region and must be of varying depths (Brenneisen 2006).
USA – Illinois – Chicago	• Energy Conservation Code requires roofs to achieve a minimum albedo of 25 %. Although the city's policy does not state as such, it is accepted that green roofs are a practical way of meeting this requirement; • Encourages developers by allowing them to develop at higher density than policy would otherwise allow if at least 50% or more than 160 m^2 of the roof surface is covered by vegetation; • Operates a grants scheme and storm water retention credits (Lawlor *et al.* 2006; Grant *et al.* 2006 cited by Gedge and Newton 2008).

Table 2.1 – Selected current green roof policies by country, state or city (continuation)

Country / State / City	Policies
USA – Oregon – Portland	• Floor Area Ratio Bonus - in areas where zoning regulations limit buildings' height-to-floor-area ratio, by greening all or part of a roof, a developer can add as many as 3 m to the building height for every m^2 of green roof (Liptan 2005 in Nagase and Dunnett 2012); • City-owned buildings are required to have a green roof covering at least 70 % of the roof and have a 35 % reduction in storm water management charges (Gedge and Newton 2008).

The measures applied in Basel, Switzerland, have led to the conversion of an area the size of seven football fields into green roofs within one and a half years (Reinhardt and Schaffner 1999 cited by Brenneisen 2002). Green roofs are now mandatory in the whole country on new buildings with flat roofs, and guidance is provided for the creation of different plant and animal habitats on the green roofs (Brenneisen 2006; Brenneisen 2002). It all started with a campaign in which house owners could claim 20% of the investment costs from the government if they followed the recommendations for greening the unused space on top of their buildings (Reinhardt and Schaffner 1999 cited by Brenneisen 2002).

Germany has had a 10% to 15% growth per year in the green roof industry over the past 10 years (Getter and Rowe 2006), which corresponds to an increase of approximately 13.5 million m^2 of green roofs per year (Oberndorfer *et al.* 2007). In 1989, 1 million m^2 of green roofs were installed, in 1997, 11 million m^2 and in 2001, 13.5 million m^2 of green roofs were installed (Thompson and Sorvig 2007 cited by Grant *et al.* 2003). In Berlin, green roofs are sometimes integrated into local land-use plans either as source control measures or as nature compensation measures. In 1980, the western sector of the city (before reunification), developed the "Biotope Area Factor" or "BiotopFlächenFaktor", in German, which is the ratio between "ecologically effective surfaces" (i.e. gardens, green roofs, etc) and the total land area. Different surfaces receive a value depending on their ecological effectiveness: a conventional roof scores 0 and a surface with vegetation and more than 80 cm of soil (intensive green roof) scores 0.7. This measure was developed more than 30 years ago and already recognized green roofs as a tool to reduce the environmental impact of high density urban development (Ngan 2004).

In Toronto, from February 1st, 2010, to March 1st, 2015, 260 green roofs have been created, corresponding to 196000 m^2. According to the information in the City of Toronto website (2015), a total of 444 green roofs exist in the city.

The policies in the city of Tokyo, Japan, have proven to be effective, as they have resulted in the construction of approximately 50000 m^2 of green roofs annually.

In the USA, in 2006, 285000 m^2 of green roof have been installed, which may be a small number when compared to the growth of the industry in Germany, but represents an increase of 24 % over the previous year, 2005 (Berghage *et al.* 2009). In the city of Portland (Oregon), the municipality has invested in promoting green roofs by setting the example and install them in municipal buildings, as well as holding public events on green roofs (Wolfgang and Roland 2011). In the summer of 2004, Chicago had an increase in more than 92903 m^2 in green roof commitments or implementation (City of Chicago, Department of Environment, 2004 cited by Getter and Rowe 2006).

2.3.2 The Portuguese case

In Portugal there are not any specific laws or regulations regarding the implementation of green roofs. The only legal document that can be somehow related to this thematic is the legal framework for urban rehabilitation (Regime Jurídico Da Reabilitação Urbana 2009). According to points g) and r) of the third Article of Part I of the referred document, urban rehabilitation should contribute to "promote environmental, cultural, social and economical sustainability of the urban space" and "encourage the adoption of energy efficiency criteria in public and private buildings". The General Principles of urban rehabilitation, also stated in this document in the fourth Article of Part I, refer, in point d), the "principle of sustainability, assuring that the intervention relays on a financially sustained and balanced model and contributing for the valorization of urban areas and of intervened buildings through solutions that are innovative and sustainable from the socio-cultural and environmental point of view". By our interpretation, these statements reveal a concern with the adoption of new technologies that may contribute to a better urban environment.

Further ahead the document describes the financial aspects of the rehabilitation interventions and entitles the municipalities to decide on the attribution of financial supports (First point of Article 75º of Chapter VIII of Part II of Regime Jurídico da Reabilitação Urbana 2009).

The support for rehabilitation interventions provided by the Municipality of Lisbon exists as tax incentives or fee reductions. The tax incentives can be even higher if the intervention has a recognized national public interest (CML 2015a). The fees may be reduced during the rehabilitation works (for occupation of public space, etc) and the owner is given the possibility to amplify the building until 250 m^2 without paying any extra fees. The rehabilitation operation promoted on municipal heritage buildings are free of fees (CML 2015b).

A will to promote the introduction of environmentally friendly and green solutions seems to be present, but mostly as general principles and goal. No specific regulation has been developed, nation wide or at the municipality level, in order to promote the construction of green roofs or any other structures that may benefit biodiversity, storm water management or energy saving.

2.4 Green Roofs as part of the urban green infrastructure – opportunities and limitations

Barker (1997), defines green networks as "natural, or permanently vegetated, physically connected spaces situated in areas otherwise built up or used for intensive agriculture, industrial purposes or other intrusive human activities".

Magalhães (2001) establishes a difference between urban green infrastructure and urban ecological infrastructure. For this author, the urban green infrastructure includes every space covered by vegetation, while the urban ecological infrastructure, a subset of the first one, aims to "ensure a higher biological value and protect the systems that are fundamental to the ecological balance of the city" and is made of different biotopes and corridors connecting them, creating a *continuum naturale* (Magalhães 2001) . The urban ecological infrastructure can also be considered as a primary urban green infrastructure, while the secondary is composed by the green spaces integrated in the urban space (Magalhães 2001).

Both authors agree that those structures are characterized by their connections or links that materialize into green corridors. The goal of this section is to reflect on whether green roofs should or should not be integrated in the urban green or ecological infrastructure, given their discontinuous nature.

Both Magalhães (2001) and Barker (1997) have reflected on subjects that can be compared to green roofs. Magalhães (2001) defends the importance of block patios for the urban ecological infrastructure in areas of high density and alerts for the necessity of maintaining an adequate permeability of the ground. For this author, these structures are "islands" or "points" that, despite of being discontinuous, still provide habitats for birds and represent a connection between the atmosphere and the subsoil (Magalhães 2001). Barker (1997) highlights the fact that for many species adapted to the urban space, a "close mosaic of stepping-stone habitat patches" may not be as different from a continuous corridor as expected. For this author, these "habitat-patches" may be valued more for their vegetation structure, small scale topography and micro-habitat richness than for their size.

Although the continuity principle is of high importance for urban planners, it should be beared in mind that, in densely urbanized areas where the creation of green corridors is limited, the sites that provide the opportunity to create green spaces should be explored. Structures like block patios and green roofs fit in this category.

Considering a long term perspective, redevelopment may give opportunities to create the desired connections between the nodes that can be built today.

What is, however, theme for further reflection is the fact that, while block patios are directly connected to the ground, green roofs are deprived from the dynamics provided by this relation, not allowing the water to directly infiltrate, for example, which can be a benefit from the storm water management point of view. As green roofs offer an opportunity to insert vegetation and wildlife in a dense urban space, where the ground is no longer available, it is important to keep the notion that they do not replace nature. Contrary to parks or gardens, the green roof is limited by the lifetime of the building and by its height, loosing physical or even visual (depending on the building structure) connections with the surroundings. On the other hand, these isolated spaces, depending on the type of use they are subjected to, enjoy a privileged relation with the sky and with the open space above the, sometimes suffocating, streets of the city. It is also free from many disturbances, which can be a booster for biodiversity.

The British architect Norman Foster (Johnston and Newton 2004) once said: “I always think that it is somewhat tragic that when you contemplate the view of any city from a high-rise building that the possibility of recreating the ground level site at the top of a building is generally squandered”. According to what has been said above, this is exactly the misconception of the green roofs function that should be avoided. By constructing a building, the lost nature cannot be replaced. Green roofs, despite their incontestable benefits for the urban environment, should not pretend to work as a fake substitute of nature.

The Portuguese law defines the concept of "municipal ecological infrastructure ", in point one of the eleventh Article of Chapter III of the Implementing Decree nº 11/2009 of May 29th, as "the group of areas that, for their biophysical or cultural characteristics and for their ecological continuity, have as main function the contribution for the ecological balance and for the environmental and landscape protection, conservation and valorization of the rural and urban spaces" (*Decreto Regulamentar nº11/2009 of May 29th*). This article is in disagreement with the reflection exposed before, as it seems to consider the ecological continuity as a determinant factor for the integration of a site in the ecological network, therefore excluding green roofs. Although, from the perspective here presented, that condition would also implicate the exclusion of parks or public gardens that do not communicate with other ecologically valuable areas. In what concerns function, green roofs fulfill the requirements of the Implementing Decree.

Despite their limitations, green roofs offer, in our perspective, opportunities that justify their integration in the urban green infrastructure. They are not nature, so should not be part of the primary green infrastructure, or ecological infrastructure, but including them in the secondary green infrastructure seems very appropriate. The integration of green roofs in the urban green infrastructure could be a driver to change the approach that has been used towards them, establishing these structures as a way to achieve environmental benefits, instead of just an embellishment for private buildings.

2.5 Hydrological performance of green roofs in urban areas

The hydrological dynamics of green roofs have been studied, at least, since 1985, by German investigators Ernst and Weigerding (Getter and Rowe 2006). Since then, many studies have been published, most of them after 2000, from many countries around the world.

Among the studies referred in this work, five are from the United States of America, three from Italy, three from the United Kingdom, two from Canada, two from Australia, one from New Zealand, one from Korea and one from France. The comparative analysis of the results obtained in those experiments must be cautious, due to the variability of climate and experimental set up conditions (substrate composition, plant species, green roof layers, etc). The fact that most studies had the overall goal to understand the response of green roofs to rainfall, some intended to compare the effectiveness of different substrates, some the performance or survival of different types of vegetation, some the roof slopes, some the rainfall pattern, etc. A table summarizing the gathered information is available in Appendix II.

VanWoert *et al.* (2005) developed a study in the Michigan State University, USA (temperate climate (City-data 2015)), in which they compared a gravel roof with a green roof vegetated with a *Sedum* mat and with a substrate-only green roof. They also compared green roofs with different slopes and substrate depths. On the first group, the vegetated test bed showed a higher cumulative rainfall retention (60.6 %) when compared to the substrate-only (50.4 %). The differences were even more evident for heavy rainfall events. Between the various slopes and substrate depths, the test bed combining the lowest slope (2 %) with deeper substrate (40 mm) showed the best performance for all of the studied types of rainfall (mean retention was 87 %).

In the study of Hathaway *et al.* (2008) in North Carolina, USA (humid, subtropical climate (City-data 2015b)), two different substrate depths, 75 and 100 mm, were compared (the test plots had the same substrate type and were covered by succulents). Both performed the same in terms of retention, but the deepest substrate layer had the best rainfall peak attenuation results (88 % against 77 %).

Berghage *et al.* (2009) verified drastic differences between summer and winter rainfall retention results (95 and 20 % respectively) in their field study at the Centre for Green Roof Research at Pennsylvania State University, USA (lies entirely within the humid continental zone but climate varies according to region and elevation (City-data 2015c)). According to the results of this study, during summer time, rainfall events were more disperse over time, so the substrate had enough time to dry and recover its retention capacity.

Fassman-Beck *et al.* (2013) compared vegetation covers (Sedum sp., native plants and mix of native and non-native plants) and substrate depths and found the best cumulative retention results (66 %) on the test plot covered by *Sedum* sp., contrary to what had been observed in most of previous studies. However, in this study, the green roofs under test were located in different buildings, although all in Auckland, Australia (subtropical climate), hampering the comparison of the results. One of the experiment sites had two green roof test plots with the same vegetation cover and substrate type but with different depths, 100 and 150 mm. Here the best performance corresponded to the deepest substrate, which had 57 % cumulative retention, 66 % median retention and 74 % median peak attenuation, while the shallowest substrate resulted in 48 % cumulative retention, 55 % median retention and 73 % median peak attenuation.

Harper *et al.* (2014), in a study that took place in Missouri, USA (continental climate, with considerable local and regional variation (City-data 2015a)), compared green roof test plots vegetated with succulents, with others without vegetation and obtained an increase of 20 % in the retention capacity on the vegetated ones.

On another approach, Razzaghmanesh and Beecham (2014) installed an experiment in Adelaide, Australia (hot Mediterranean climate) to compare intensive (substrate 300 mm deep) and extensive (substrate 100 mm deep) green roofs, covered with a mix of four species of native plants. These authors obtained higher retention and runoff delay results from the intensive test plots (mean of 88.62 % and 17 hours respectively) then, from the extensive ones (with 74.02 % mean retention and 3 hours mean runoff delay). The rainfall peak attenuation range of results was similar between intensive and extensive plots.

Lee *et al.* (2015), in Seoul, Korea (cold and temperate climate [Climate-Data 2015]), also compared substrate depths, 150 and 200 mm, and had clearly different rainfall retention results intervals - in the shallower substrate they varied from 13.8 to 34.4 %, while in the deeper the variation was between 42.8 and 60.8 %.

Yilmaz *et al.* (2015) compared different combinations of substrate depths (80 mm or 120 mm) and vegetation covers (no vegetation, *Sedum album*, *Festuca glauca* or *Dianthus deltoides*) in their study in Nantes, Western France (oceanic climate). The best mean retention result occurred for *Dianthus deltoides*, although the substrate was only 80 mm deep, followed by the combination of the same plant with 120 mm substrate depth. The lowest mean values corresponded to the unvegetated and to the *Sedum* sp. plots, both with 80 mm substrate depth. These authors also observed that the hydrological behaviour was similar for both substrate depths under light or medium rainfall, but for heavy rainfall, the 120 mm retained more than the 80 mm regardless of the vegetation.

Many studies intended to compared the hydrological behaviour of traditional roofs (asphalt, gravel, etc) with green roofs and the rainfall retention were consistently higher for the green roofs despite of roof slope or other conditions (VanWoert *et al.* 2005; Berghage *et al.* 2009; Yilmaz *et al.* 2015).

On a global analysis, the lowest rainfall retention registered on the reviewed literature was 34 %, in Stovin (2010), who had a substrate depth of 80 mm, which can be considered relatively shallow in comparison with most of the other studies. Overall, the mean rainfall retention results were above 50 %, showing that green roofs can, in fact, contribute to reduce the storm water flowing into the drainage systems under different conditions and in different locations.

However, it was not found, among the revised bibliography, any study taken under the Mediterranean climate in which the objective had been to study the performance of different native plants, with reduced water demands during dry months.

2.6 Green Roofs in the Mediterranean climate

According to the classification of Köppen, the Mediterranean climate is characterized by mild wet winters with low solar irradiance and hot dry summers with high solar irradiance. However, the intensity of summer drought, as well as the annual total rainfall, vary considerably from location to location (Hobbs *et al.* 1995).

In Mediterranean climate the rainfall is concentrated in the season of cooler weather, meaning that the water availability is lower when the temperatures are higher and that the plant's activity is lower when the needs of water retention are higher. This constitutes the biggest limitation of green roofs under Mediterranean climate.

During summer time, water is a precious resource in regions with Mediterranean climate and, therefore, the conception of green spaces must be focused on sustainability, considering water scarcity for irrigation. When the water use must be allocated, domestic use is prioritized, while the irrigation of green spaces is one of the first to be excluded. Climate change is expected to cause more and more intense droughts, due to its impact on rainfall intensity and duration, creating more situations in which the water use will have to be thoughtful (EEA 2009; Bates *et al.* 2008). On the other hand, during winter, there can be large volumes of rainfall in short periods of time, many times causing floods. Given these factors, the plant selection is decisive for the success of a green space and green roofs are no exception.

The plants most commonly used on green roofs, irrespectively of the climate, are succulents, especially *Sedum* sp.. Despite its great resistance to drought and to the harsh conditions of the green roof, some authors have already explored the advantages and limitations that the introduction of other types of vegetation may offer, as it was referred in section 2.2.

Dvorak and Volder (2010) alert to the fact that the plants on green roofs are exposed to similar environmental conditions as the species that are native to the region. Therefore, they suggest that the survival of the green roof vegetation is correlated to the similarity between the conditions of the roof and of the plants' original habitat, most of all its hydrological dynamics and cycling of nutrients. The thickness and water holding capacity of the substrate needs to suit the vegetation requirements as well as the structural capacities of the building. Dvorak and Volder (2010) found that drought tolerant native and introduced herbaceous plants can be used on green roofs, but deeper substrates and some irrigation may be necessary, when compared to the exclusive use of succulents.

Oberndorfer *et al.* (2007) also suggest that native plants may be interesting to study and use as vegetation for green roofs, due to their adaptations to the local conditions.

According to Platt (2004), cited by MacIvor and Lundholm (2011), native plant communities can restore some of the ecology of densely urbanized areas and mitigate the effect of impervious surfaces, if green roofs are properly designed and installed.

Many Mediterranean species (xerophytes) have morpho-functional and physiological adaptations: changes on the leaves (imbricate or often linear, with a thick, waxy cuticle, silvery colour, sunken stomata), on the roots (deep rooting, hairy surface, fast development of young plants, symbiotic relationships), decreased photosynthesis and loss of leaves due to drought, incident solar radiation and high summer temperatures (Davis and Richardson 1995). Therefore, the use of native plants can significantly reduce the costs of maintenance and the need for irrigation, especially in a climate like the Mediterranean one, where the water is scarce in the summer. Native plants can also play a major role in attracting wildlife (Grant *et al.* 2003), as they help to mimic, on the rooftop, habitats that appeal to local insects and birds, among others.

It is true that green roofs have been mainly studied and developed in countries where the climate favours vegetation growth. The table in Appendix II summarizes different studies, including their location, and, when possible, climate, that may confirm that trend. In the Mediterranean countries, there is still a lack of scientific studies on this matter (Fioretti *et al.* 2010) and, particularly on plant selection. Plant selection is critical in Mediterranean sites and the use of native plant species may be a good choice, as they can survive without irrigation due to an increased resiliency of the system.

3. MATERIALS AND METHODS

3.1 Study site

This study was conducted at the rooftop terrace of the Herbarium building of Instituto Superior de Agronomia, in Lisbon, Portugal (38°42'28''N, 9°11'0,4''W). The building has three floors and a traditional gravel rooftop terrace.

The city of Lisbon has a typical Mediterranean climate, of the type "Csa", according to the classification of Köppen-Geiger (IPMA 2015a), which corresponds to a temperate climate with hot and dry summers and precipitation concentrated between October and April. The climatic characteristics of the city depend on regional geographic factors such as latitude, proximity to the Atlantic Ocean and to the Tagus River and topography (CML 2010). Table 1 specifies some climatic characteristics.

Table 3.1 - Characteristics of Lisbon's climate 1981-2010 (IPMA 2015b; IPMA 2015c; CML 2010)

Variable	Values
Temperature	
Average annual temperature	16 °C
Lowest value of minimum temperature	March (0.2 ºC)
Lowest average minimum temperature	January (8.3 ºC)
Highest value of maximum temperature	August (41.8 ºC)
Highest average maximum temperature	August (28.3 ºC)
Lowest average average temperature	January (11.6 ºC)
Highest average average temperature	August (23.5 ºC)
Rainfall	
Average annual rainfall	572.8 mm
Highest average rainfall	November (127.6 mm)
Lowest average rainfall	July (4.2 mm)
Highest maximum rainfall in one day	February (118.4 mm)
Wind	
Predominant wind - Winter	Northeast
Predominant wind - Summer	North
Predominant wind – intermediate seasons	Southwest, West, Northwest

3.2 Rainfall event definition

Independent rainfall events were, at the beginning, defined as continuous or intermittent rainfall periods that were separated by a dry (without rain) period of at least six hours. This procedure was later on revaluated according to the runoff behaviour. If the runoff event resulting from a rainfall event lasted until the beginning of a new rainfall event, the two were combined into one single event. The six hour period was chosen since it is the most usual amongst the literature (VanWoert *et al.* 2005; Getter *et al.* 2007; Hathaway *et al.* 2008; Stovin *et al.* 2011; Berretta *et al.* 2014; Razzaghmanesh and Beecham 2014), therefore allowing comparison between results obtained in this study and others.

3.3 The experimental setup

3.3.1 The test beds

Twelve test beds were set at the experimental site (Figure 3.1). Each test bed intended to simulate a green roof of different configuration, including different substrate compositions and vegetation covers. The test beds consisted of 2,5 × 1 × 0,2 m aluminium containers, supported by a stainless steel structure with four legs, 1 m high relatively to the roof surface (Figure 3.2).

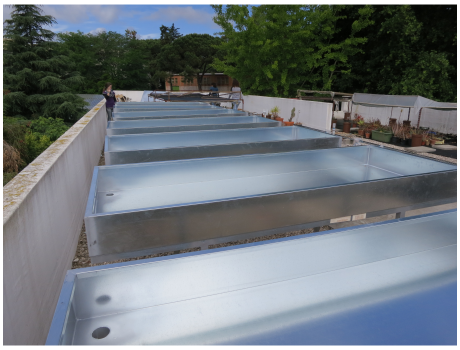


Figure 3.1 – Test beds at the experiment site.

All the test beds had a slope of 2,5%, in order to enable a proper drainage of the runoff water, and face south, therefore receiving the best sun exposure.

Figure 3.2 – Test bed.

The bottom of the test beds had multiple layers of material, applied according to what is the usual procedure on real context green roofs. However, some differences have to be referred, since in these simulations there was no need to rooftop waterproofing, for example. The bottom layer was a protection and retention non woven blanket (SSM45 ZinCo, Barcelona, Spain), commonly known as geotextile fabric, that intends to protect the layers below (when they exist, in real rooftop situations) from the plants' roots and from the pressure applied by the weight of the materials or by walking (Figure 3.3). According to the manufacturer, this blanket is made of high quality fibbers, resistant to decomposition and tested according the European standard EN ISO 13428. It is 5 mm thick, weights 470 g m^{-2} and has a water holding capacity of approximately 5 L m^{-2}.

Above this blanket there was a drainage layer composed by polyethylene plates (Floradrain® FD25-E, ZinCo, Barcelona, Spain) (Figure 3.4), which collects the water drained by the substrate in their cavities, and allow it to runoff according to the slope of the surface. The drainage layer is 25 mm high, has a water retention capacity of approximately 3 L m^{-2}, weights approximately 1700 g m^{-2} and respects the European standard EN ISO 12958, according to the technical information provided by the manufacturer.

Above the drainage layer and right below the substrate, a filter system, a non woven blanket (SF ZinCo, Barcelona, Spain), was set, this one thinner than the other below, whose function is to prevent the substrate particles from obstructing the drainage layer (Figure 3.5). According to the manufacturer, this layer has an approximate weight of 100 g m^{-2} and respects the European standards EN ISO 12236, EN ISO 11058 and EN ISO 1295. Further information on the green roof layers is available in Appendix 3.

Both non-woven blankets were set covering the whole bottom and sides of the test beds, in order to ensure that no substrate would penetrate in the drainage layer. Every time that more than one sheet had to be used, they were overlaid by, at least, 10 cm.

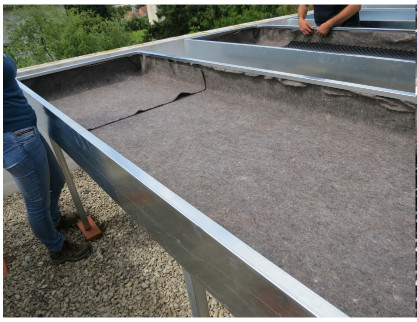


Figure 3.3 – Non woven blanket (SSM45).

Figure 3.4 – Drainage layer (FD25).

Figure 3.5 – Top non woven blanket (SF).

3.3.1.1 Drainage system

At the Southwest corner of each test bed, there was a hole with a drop tube, (Figure 3.6) through which the runoff water would be conducted to a measuring device. The runoff water would be collected by the drainage layer, referred above, and would move according to the 2,5% slope of the test bed. It must not be forgotten that the non-woven blanket layers have great capacity to retain water, therefore being elements of considerable impact in the water related results of this study.

Figure 3.6 – Drainage hole.

3.3.1.2 Growing media and plant establishment

The test beds were filled with two different types of substrate, each one with its particular characteristics.

The substrates used in this experiment were provided by the Portuguese company LandLab (substrate characteristics provided by the company are available on Appendix 6). Besides the usual mineral components (clay, silt and sand), the substrates also present pine bark humus, peat, expanded clay and volcanic rock.

Three species of native plants, well adapted to Mediterranean climate conditions – *Rosmarinus officinalis* L., *Brachypodium phoenicoides* (L.) Roem. & Schult. and *Lavandula stoechas* L. subsp. *luisieri* – and five species of moss, with tolerance to dissecation - *Homalothecium* sp., *Brachythecium plumosum, Pleurochaete squarrosa, Pleurochaete* sp. and *Neckera* sp. – were used. The native plants were provided by Sigmetum, a Portuguese company specialized in the production and experiment of native plants. For further details about the selected native plants consult Appendix 4. The bryophytes were collected in nature. The plantation works took place during July 2014. The plants were placed in the test beds in three rows, lengthwise, each row including 6 or 7 specimens.

3.3.2 Green roof treatments

The combination of different growing media and different plants originated six experimental treatments distributed by nine test beds. A substrate only test bed, without vegetation, was also prepared, as a reference. Table 2 describes the treatment applied to each test bed, which are numbered form 1 to 9, from East to West at the experimental site.

Table 3.2 – Green roof treatments

Test bed	Substrate	Vegetation
1	S2	Mosses
2	S1	Mix of plants and mosses
3	S1	*Rosmarinus officinalis*
4	S1	*Brachypodium phoenicoides*
5	S1	*Rosmarinus officinalis*
6	S1	*Brachypodium phoenicoides*
7	S2	*Lavandula stoechas* subsp. *luisieri*
8	S2	Bare soil
9	S2	Mosses

In this study, it was not found the need to replicate a traditional roof for comparison with the green roof systems, once many previous studies have done this comparison. The hydrological performance results were consistently better for green roofs, despite of roof slope or other conditions (VanWoert *et al.* 2005; Berghage *et al.* 2009;Yilmaz *et al.* 2015). Therefore, it was considered that there was no longer the need to perform that kind of study.

3.4 Data collection and analysis

3.4.1 Substrate characterization

In order to characterize the growing medium, samples were taken and sent to the INIAV (Instituto Nacional de Investigação Agrária e Veterinária) laboratory.

The collection of samples (illustrated by Figure 3.7) was divided in three groups, using three different containers: small cylinders (5 cm diameter), large cylinders (10 cm diameter) and plastic bags. For each type of substrate, three undisturbed samples were collected on small cylinders, in order to analyse the bulk density, the field capacity and the total porosity. Two undisturbed samples of each substrate type were also collected using the large cylinders, for the saturated hydraulic conductivity determination. The plastic bags samples were composed by three disturbed repetitions (gathering samples from three different locations in the test beds, in order to minimize the errors associated to spatial variability). The determinations included the organic matter content and other chemical parameters like pH, nitrogen, potassium and phosphorus contents, the pore size distribution (content in sand, silt and clay) and the permanent wilting point.

In the undisturbed samples, the maintenance of the substrate structure, as it is on the study site, is imperative due to the fact that the analysed parameters depend on the macro porosities of the substrate, which would be destroyed by inappropriate handling, leading to altered results. On the other hand, the analysis of characteristics such as the organic matter content, texture and permanent wilting point, depend only on the micro porosities of the substrate, which are not compromised by handling or chance in space configuration, as they are independent of the structure. Therefore, for the analysis of these parameters, the collection of samples in plastic bags does not

Figure 3.7 – Substrate sample collection – steps 2, 5 and 6.

compromise the results.

To assure a minimum disturbance of the samples referred, the following collecting procedure was used:

1. Wetting of the substrate (in order to maintain structure, otherwise, it would fall apart when pulling out the cylinders);

2. Careful vertical even insertion of the cylinder into the substrate;

3. Slight dig of the surrounding substrate, with caution so the sample would not be modified;

4. Coverage of the top end of the cylinder with cling film, held by a rubber band;

5. Insertion of a gardening shovel under the cylinder, far enough from it so it would not be disturbed;

6. Removal of the cylinder and coverage on the down end with cling film and rubber band.

According to the INIAV laboratory, the mechanical analysis of the substrate was carried out with the pipette method, following the methodology described in Silva *et al.* (1975) and using the limits of the scale of Atterberg, recommended by the International Union of Soil Science (IUSS).

In what refers to the hydrodynamic properties of the substrates, the field capacity was determined using the sand box set up (Stakman 1974). For the permanent wilting point, was used the method of the pressure plate (Richards and Fireman 1943). The saturated hydraulic conductivity was determined by the constant load method (Stolte 1997).

Nitrogen content was determined by Kjeldahl method (Rutherford *et al.* 2008), potassium and phosphorus content by the Égner-Riehm method (Tiessen *et al.* 2008; Ziadi *et al.* 2008) and pH in water was determined by the method described in Hendershot (2008).

3.4.2 Soil moisture measurements

The substrate moisture content was measured with water content reflectometers (CS616 WCR, Campbell Scientific, Utah, USA) (Figure 3.8). The water content reflectometer consists of two stainless steel rods connected to a printed circuit board. A shielded four-conductor cable is connected to the circuit board to supply power, enable the probe, and monitor the pulse output (Campbell Scientific 2006).

Figure 3.8 – Water content reflectometer.

According to the user manual, “The fundamental principle for CS616/CS625 operation is that an electromagnetic pulse will propagate along the probe rods at a velocity that is dependent on the dielectric permittivity of the material surrounding the line. As water content increases, the propagation velocity decreases because polarization of water molecules takes time. The travel time of the applied signal along two times the rod length is essentially measured. A calibration equation converts period to volumetric water content" (Campbell Scientific 2006).

Figure 3.9 – Tipping buckets.

As in every method, the results of the WCR are suitable to present errors. The errors can originate from wrong probe insertion, variability between probes (± 2% volumetric water content) or they can be affected by the electrical conductivity of the media between the rods.

In this study only relative water content values were used, by comparing each recorded data to the maximum value recorded.

Figure 3.10 – Tipping bucket runoff gauge, drop tube and plastic wrap.

The probes were buried in the substrate during its placement, at a depth of approximately 7,5 cm, halfway to the surface, parallel to the bottom of the test bed. The wires were connected to a CR1000, Casella, London, UK, data logger, programed to collect data every 10 seconds and record average values every 30 minutes.

3.4.3 Rainfall and runoff measurements

For each test bed, a tipping bucket rain gauge was positioned under the drop tube through which the runoff water drained (Figure 3.9). From the drop tube to the tipping bucket were set cone shaped plastic wraps, in order to ensure that no rainfall water would enter the measuring device, altering the results for the runoff water, and to prevent the water flow from being diverted by the wind (Figure 3.10). A tipping

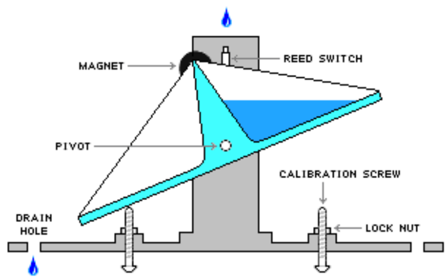


Figure 3.11 – Detail of the tipping bucket's measuring device (weathershak.com).

bucket rain gauge has a funnel shaped water-receiving area, which collects the water, in this case, drained from the system, leading it to pass through a mesh tube, in order to exclude the larger particles, followed by an outlet nozzle, that diminishes the speed of the runoff water. Underneath there is a basculanting piece, composed of two opposite small containers, the tipping buckets, with known capacity (Figure 3.11). Every time one of the small buckets reaches maximum capacity, the piece tips, and the full container is lowered, as the empty one is raised and starts to receive the water, and so on. These devices were connected to a data logger (CR10X and CR1000, Casella, London, UK) that received a signal every time the buckets tipped, due to a magnet that closes a reed switch, so it may be possible to know the number of tips, within a period of time, as well as the amount of water drained. The data logger recorded the sum of the number of tips every 2 minutes.

In this experiment, two different types of tipping bucket rain gauges were used: 0.2 mm (W5724 Casella, London, UK) and 0.5 mm capacity (W5720 Casella, London, UK). The dynamic calibration of these devices is needed because at each tip there is a loss of fluid that is not accounted. During the transition from one small bucket to another, there is a certain amount of water that will not fall in any of them. It is essential to find a correction factor, so the results of the investigation are not compromised.

The mentioned correction factor is determined by, after appropriate levelling of the device (by adjusting three levelling screws), pouring a known amount of water into the gauge and counting the number of tips.

Knowing the area of the reception funnel, the capacity of the small buckets and the number of tips, it is possible to establish a relation between the registered amount of water and the poured amount of water, obtaining the correction factor.

3.4.4 Data analysis

In order to analyse the collected data, some transformations were done to the values outputted by the data loggers, so the data became usable for calculations and statistical analysis.

Regarding runoff data, the data logger output, VDL, was in number of tips per 2 minutes. These values were converted into millimetres, on a test bed area basis, per 2 minutes, R_2, as follows:

$$R_2 = \frac{VDL \times F_c \times C_{TB} \times A_B}{A_{RG}} \tag{1}$$

where F_c is the calibration factor (determined as described in section 3.3.3), C_{TB} is the capacity of the tipping bucket (mm), A_B is the area of the test bed (2.5 m^2) and A_{RG} is the area of the rain gauge (0.0385 m^2).

The relative water storage, WS_R (%) in the substrate at the beginning of a rainfall event was calculated from the water content measurements as follows:

$$WS_R = \frac{WS}{WS_{max}} \times 100 \qquad [2]$$

where WS (mm) is the actual water storage at the beginning of the rainfall event, calculated as:

$$WS = \theta \times D_S \times 10 \qquad [3]$$

with θ the water content ($cm^3\ cm^{-3}$), measured with the reflectometers, and D_S the substrate depth (15 cm).

WS_{max} (mm) is the maximum amount of water that can be stored in the substrate, calculated as:

$$WS_{max} = \theta_S \times D_S \times 10 \qquad [4]$$

where θ_s is the water content of the substrate at saturation, in $cm^3\ cm^{-3}$.

In order to study the relations between rainfall and runoff and the effect of the test bed treatments, four variables were set for each rainfall event: rainfall water retention, runoff delay, peak attenuation and peak delay.

Rainfall water retention, R (%), was calculated as:

$$R = \frac{d_{RF} - d_{RO}}{d_{RF}} \times 100 \qquad [5]$$

where d_{RF} is the total rainfall depth (mm) and d_{RO} is the total runoff depth (mm).

Runoff delay, RD (h) is the difference between the time when the runoff starts, T_{RO}, in hours, and the time when the rainfall starts, T_{RF}, in hours:

$$RD = T_{RO} - T_{RF} \qquad [6]$$

Peak attenuation, PA (%), compares the precipitation and the runoff peaks (maximum values registered for an event) and is defined as:

$$PA = \frac{I_{RF} - I_{RO}}{I_{RF}} \times 100 \qquad [7]$$

where I_{RF} is the maximum rainfall intensity in 10 minutes of an event (mm h^{-1}) and I_{RO} is the maximum runoff intensity in 10 minutes of the same event (mm h^{-1}). The maximum intensity in 10 minutes (I_{10}, mm h^{-1}) was determined by calculating the mean intensity each 10 minutes since the beginning of the event and then selecting the maximum value for the whole event.

Peak delay, PD (h) is the difference between the time to the runoff peak, TP_{RO}, in hours, and the time to the rainfall peak, TP_{RF}, in hours:

$$PD = TP_{RO} - TP_{RF} \quad [8]$$

Throughout the study, when a test bed achieved full retention, meaning that there was no runoff, the retention and the rainfall peak attenuation were 100 %. The analysis of the runoff delay and peak delay presented some challenges because, when the referred scenario occurred, these variables were considered infinite. Therefore, it was incorrect to compare between test beds when some produced runoff and other did not, influencing the calculation of some statistical indicators as the average. To overcome this difficulty, the RD and PD results were at first ranked based only on the number of events that had not produced runoff, meaning that the best performing treatment would be the one with a larger number of events with 100 % retention, despite of the RD and PD values on the rest of the events. Then, to assure that the comparison between treatments was reliable, RD and PD values for the events in which at least 4 (out of 6) treatments had produced runoff were analysed in section 4.4.2.1. For the analysis in section 4.4.2.2, and again to overcome that difficulty, the comparison between treatments was made by the median values.

Throughout the analysis, test beds with equivalent treatments (same substrate and same vegetation cover) were combined and the resulting average was used as reference. Thus, the analysis focus on 6 different combinations of substrate and vegetation cover, although there were 9 test beds.

3.4.5 Statistical analysis

All the statistical analyses and graphs presented in this work were done in spreadsheets (Microsoft Office Excel for Mac 2011) and/or the RStudio software (Version 0.98.1062 – © 2009-2013 RStudio, Inc.).

Most of the histograms presented are variable bin width histograms, i.e., they were drawn based on grouped data in variable width intervals (cells) and, therefore, the area associated with each rectangle represents the relative frequency of that cell. Thus, the histogram is an estimate of the probability distribution (density function) of the continuous variable under study.

The effect of the rainfall characteristics in the runoff response was analysed by an estimate of the mean value of each variable under study (R, RD, PA and PD) and by a 95 % confidence interval for the mean. All these calculations were based on the assumptions that the sample in each rainfall class is random and that it comes from a normal population.

4. RESULTS AND DISCUSSION

The data collected from the experimental set up, referring to rainfall, runoff and soil moisture, as well as the data supplied by the INIAV laboratory, regarding the substrate characteristics, were, at first, analysed *per se* and, only after, the possible relations between them were explored.

These two separate analyses were fundamental to understand how the changes on the initial conditions (rainfall, substrate, vegetation) between test beds influenced their response, which translated into the runoff data.

4.1 Substrates

The chemical and physical properties of the substrates are summarized in Tables 4.1 and 4.2. Detailed laboratory results are presented in Appendix 6.

Table 4.1 – Substrate chemical properties

Substrate	pH	OM (%)	N (g kg^{-1})	K_2O (mg kg^{-1})	P_2O_5 (mg kg^{-1})
S1	5.15	73.15	6.22	600	184
S2	5.14	19.85	1.59	720	260

pH measured in water; OM – organic matter; N – nitrogen; K_2O – potassium; P_2O_5 – phosphorus

Substrate 1 (S1) presents a larger proportion of organic matter compared to Substrate (S2), which is favourable for the maintenance of substrate structure. The organic matter will also gradually provide nitrogen (N) to the vegetation as it mineralizes with time. From the plant nutrition perspective, these substrates are classified as highly fertile for available potassium and phosphorus (LQARS 2006).

Table 4.2 – Substrate physical properties

	Particle Size (%)			Bulk density	Saturated density	Θ_{FC} 10 kPa	Θ_{WP} 1500 kPa	Ksat
Substrate	Sand	Silt	Clay	(g cm^{-3})		(cm^3 cm^{-3})		(cm d^{-1})
S1	80.6	3.2	9.4	0.383	0.675	0.3319	0.1535	5214
S2	81.0	13.5	4.2	0.531	0.823	0.2863	0.1360	7507

Sand (2-0.2 mm); silt (0.2-0.002 mm); clay (< 0.002 mm); θ_{FC} - water content at field capacity; θ_{WP} – water content at permanent wilting point; Ksat – saturated hydraulic conductivity

As to the mineral contents, S1 presents a higher percentage of clay, which gives it lower bulk density and higher moisture content at field capacity. On the other hand, S2 presents a higher conductivity for water at saturation.

Regarding the study of the hydrological performance of the substrates, certain substrate characteristics, as the water content at field capacity and the saturated hydraulic conductivity, should be given particular relevance so that water dynamics can be predicted. Figure 4.1 shows the moisture content in each of the substrates when a certain pressure was applied.

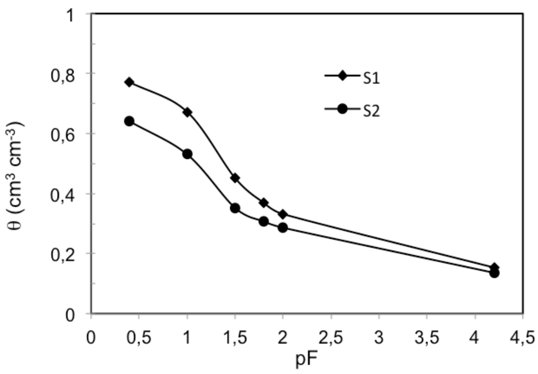


Figure 4.1 – Water retention curves for the studied substrates; θ – moisture content (cm^3 cm^{-3}) pF – logarithm of the effective pressure in cm.

S1 shows higher values concerning the water content at field capacity than S2. This means that S1 is expected be more effective in retaining water than S2. The maximum amount of water that can be stored in 15 cm of substrate is 50 and 43 mm, for S1 and S2, respectively. For this reason and in similar circumstances, S2 will produce runoff earlier than S1.

Concerning the saturated hydraulic conductivity, S2 shows higher values, meaning that this substrate type has a better ability to drain water. This parameter reinforces the previous assumption, adding the fact that S2, besides having a lower capacity to retain water, will lose the water more easily than S1. Figure 4.2 shows a sample of substrate 1 and 2 respectively.

Figure 4.2 – Substrates used in the study (left – S1; right – S2).

4.2 Rainfall

The rainfall data was recorded from September 2014 to February 2015. A total number of 46 events were recorded, with the overall characteristics described in Table 4.3. Detailed data about each event is presented in Appendix 7.

Total rainfall for the studied six months period was 584.40 mm, which was very close to the 30 years (1981-2010) mean precipitation for the same period (IPMA 2015), 572.80 mm. Figure 4.3 compares the mean monthly precipitation (1981-2010) in Lisbon with the observed monthly precipitation during the studied period and also shows the daily maximums for the same period of 30 years (the mean and daily maximum values were adapted from charts available at the Instituto Português do Mar e Atmosfera (IPMA) website).

Table 4.3 – Overall characteristics of the recorded rainfall events

	D (h)	I_{RF} (mm h^{-1})	I_{RFa} (mm h^{-1})	d_{RF} (mm)	TP_{RF} (h)
Maximum	52.77	84.00	29.54	107.40	45.00
Minimum	0.07	1.20	0.09	0.40	0.00
Mean	12.26	14.94	2.09	12.43	5.60
Median	6.43	7.20	0.70	4.00	1.17
Standard Deviation	13.86	19.55	4.68	20.11	9.86
Total	576.33			584.40	

D – duration; I_{RF} – maximum intensity in 10 minutes; I_{RFa} – mean intensity; d_{RF} – depth; TP_{RF} – time to peak

The registered rainfall during the month of November was much higher than the average, contrary to December and February, when the opposite situation occurred. The daily maximums of the study period were always lower than the ones from the 1981-2010 records, but in November they were quite close to the 30 years maximum, which reinforces the information given by the monthly depth of the rainfall, showing that November was a very wet month, with significantly intense rainfall events.

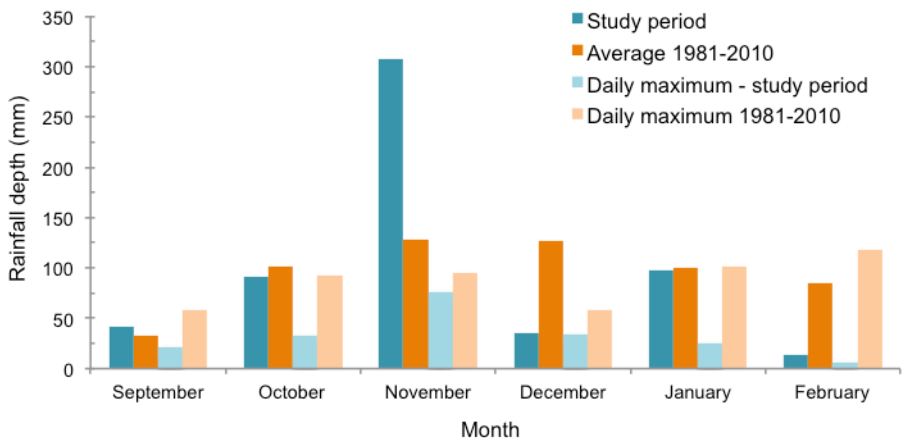


Figure 4.3 – Comparison of mean and daily maximum rainfall for the 30 years period (1981-2010) and study period monthly precipitation for Lisbon (adapted from IPMA 2015).

Figure 4.4 compares the rainfall characteristics with the Intensity-frequency-duration (IFD) curves determined with parameters from the Geophysics Institute "São Luis" obtained by Brandão *et al.* (2001). Most of the recorded rainfall events had a return period of less than 2 years. Three events were between the 2 and 5 years return period curves, one was between the 50 and 100 years return period curve, one between the 100 and 500 years curve and another above the 500 years curve. The most extreme of all recorded events, exceeds the 500 years curve. This event lasted for 46.93 hours and its maximum intensity was 84 mm h^{-1}.

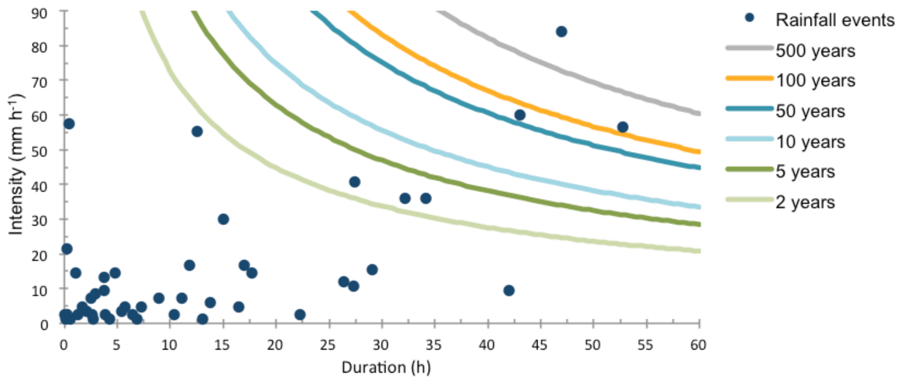
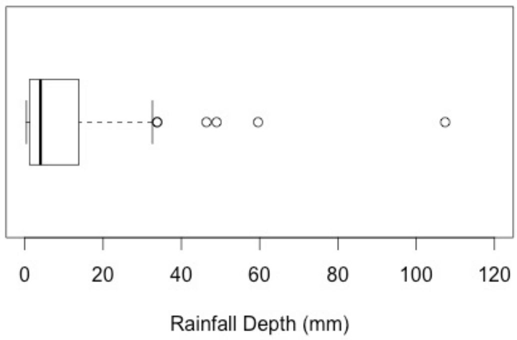


Figure 4.4 – Recorded rainfall events compared with Lisbon´s Intensity-frequency-duration curves.

The boxplot and the histogram in Figure 4.5 show that the distribution of rainfall depth was very skewed, with more than 75 % of the events with depths lower than 13.80 mm and a median of 4 mm.



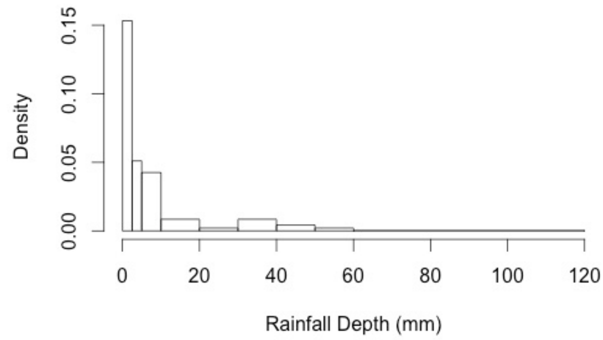
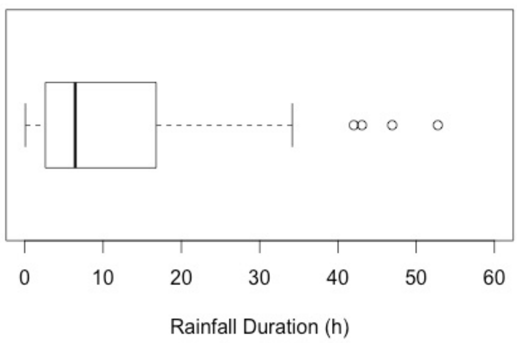


Figure 4.5 –Boxplot and histogram of the rainfall depth.

The boxplot and the histogram of the duration of the events (Fig 4.6) show a predominance of the 0 to 10 hours events and, in general, a decrease in density as the duration increased. The longest event lasted for 52.77 hours while the shortest lasted only 0.07 hours.



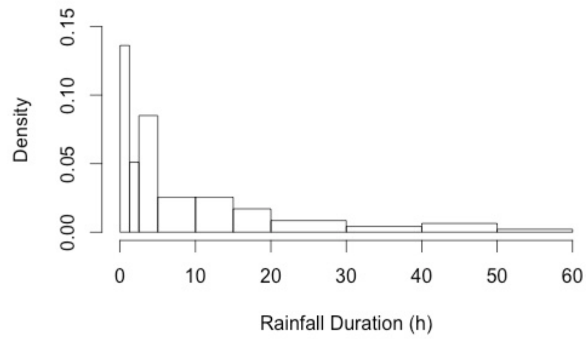


Figure 4.6 – Boxplot and histogram of the rainfall duration.

Figure 4.7 shows the distribution of the maximum intensity in 10 minutes of rainfall (I_{10}), showing a clear predominance of 0 to 10 mm h^{-1} and a decrease in frequency, as the intensity got higher. Despite the dominance of low intensity events (75 % under 15.60 mm h^{-1}), the boxplot shows several outlier records of considerably high values.

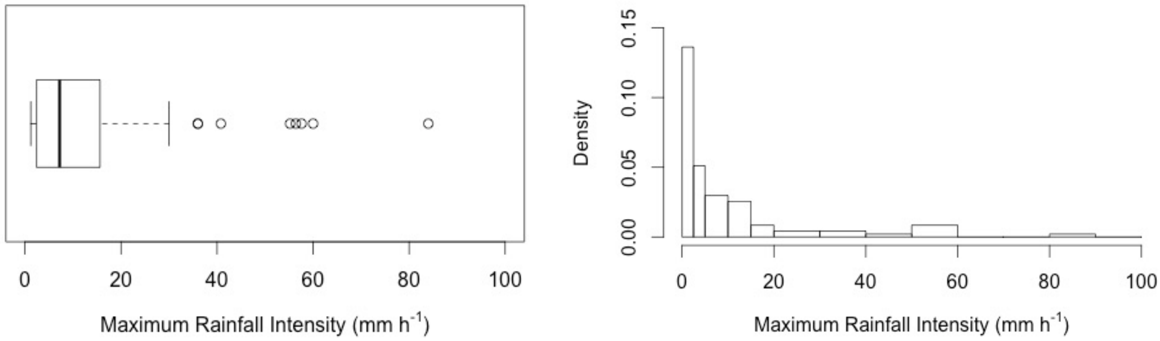


Figure 4.7 – Boxplot and histogram of the maximum intensity over 10 minutes of rainfall.

Another parameter that allowed to characterize an event was the mean rainfall intensity. To illustrate the variation of this parameter, a boxplot and a histogram were drawn. As can be seen on Figure 4.8 the distribution of this parameter is even skewer than the previous studied variables.

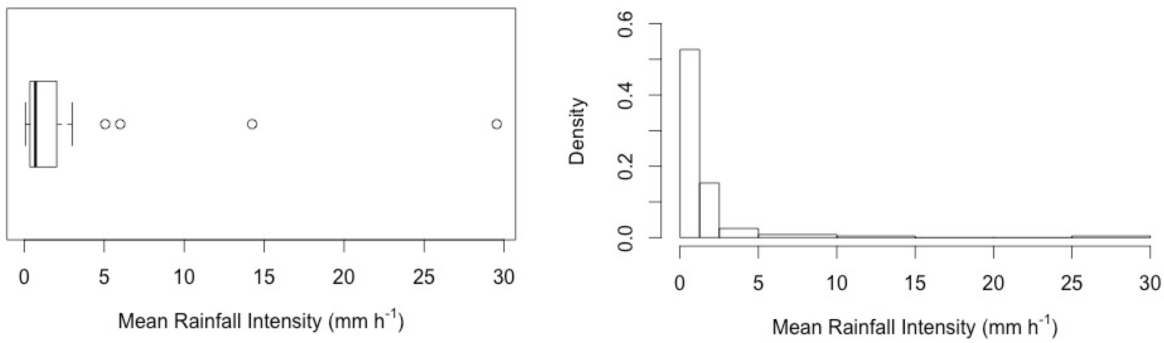


Figure 4.8- Boxplot and histogram of the mean rainfall intensity.

The majority of the events (75 %) had mean rainfall intensity lower than 2.03 mm h^{-1}, with 50 % of the events reaching 0.70 mm h^{-1} at most. There were some outlier events that reached values as high as 30 mm h^{-1}.

Finally, it was also important to evaluate the distribution of the time to peak values, defined as the time it takes for the rainfall to reach its maximum intensity. The boxplot and histogram in Figure 4.9 show that 75 % of the events took less than 8 hours, but, although there was a large range of variation (in some cases it took 40 hours or more to achieve the peak intensity), the median was 2.33 hours.

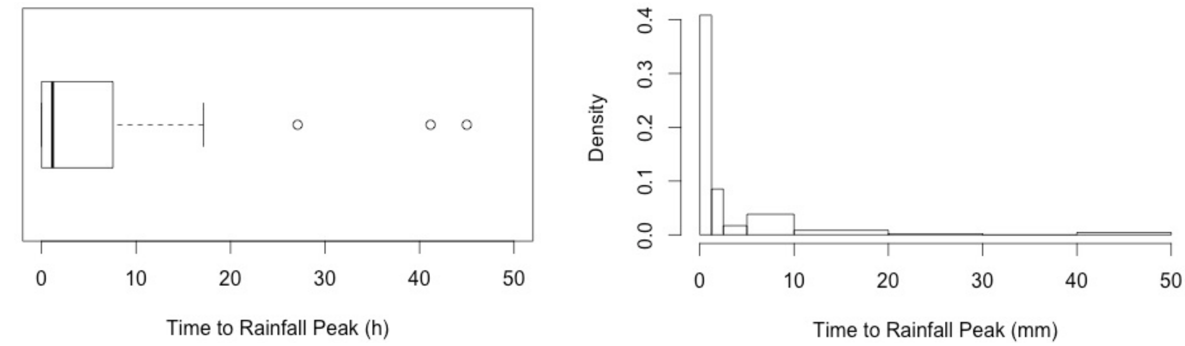


Figure 4.9 – Boxplot and histogram of the time to rainfall peak.

In order to be able to statistically analyse the recorded rainfall and runoff data, the events were grouped according to their characteristics. In VanWoert *et al.* (2005) a similar classification was made and the categories were set so the rain event samples were similar in size. In this study the categories were defined, not only to obtain similar sample sizes, but also to allow the variables to have more symmetrical distributions.

Referring to the duration of the rainfall events, they were classified as short (< 3 h), medium (3-15 h) and long (> 15 h), each class presenting 16, 17 and 14 events, respectively.

Table 4.4 presents statistical information on the duration classes, while the boxplot in Figure 4.10 illustrates their distribution.

Table 4.4 – Sample statistics of rainfall events by duration classes

Class	Mean (h)	Median (h)	Nº of events
Short	1.36	1.18	16
Medium	7.86	6.87	17
Long	30.06	27.38	14

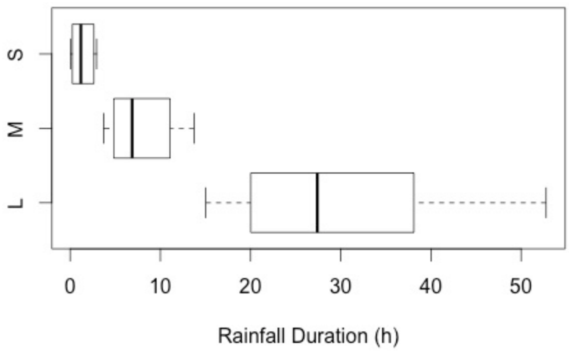


Figure 4.10 – Boxplot of the rainfall duration by classes (S – short, M – medium, L – long).

Regarding the rainfall maximum intensity, three categories were also defined. The events were classified as of low intensity (< 5 mm h^{-1}), medium intensity (5 – 20 mm h^{-1}) and high intensity (> 20 mm h^{-1}). According to this classification 22 events of low intensity were obtained, 15 of medium intensity and 10 events of high intensity. Table 4.5 and the boxplot in Figure 4.11 shows sample statistics related to the referred classes.

Table 4.5 – Sample statistics of rainfall events by maximum intensity classes

Class	Mean ($mm\ h^{-1}$)	Median ($mm\ h^{-1}$)	Nº of events
Low	2.56	2.40	22
Medium	11.20	10.80	15
High	47.76	48.00	10

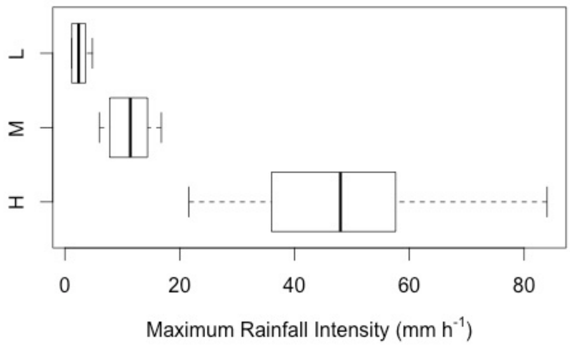


Figure 4.11 – Boxplot of the maximum rainfall intensity over 10 minutes by classes (H – high, M – medium, L – low).

Finally, the two classification factors, duration and maximum intensity over 10 minutes, were combined. Table 4.6 shows the number of events that fit in each category of maximum intensity/duration (low/short [LS], low/medium [LM], low/long [LL], medium/short [MS], medium/medium [MM], medium/long [ML], high/short [HS], high/medium [HM] and high/long [HL]). Most of the short events turned out to be of low maximum intensity and most of the long events are of high maximum intensity.

Table 4.6 – Number of events combining the classifications by duration and by maximum intensity in 10 minutes

Maximum Intensity	Duration		
	Short	Medium	Long
Low	11	9	2
Medium	3	7	5
High	2	1	7

4.3 Soil moisture

The amount of water in the substrate varied throughout the study period, depending on rainfall events, substrate characteristics, vegetation characteristics and irrigation.

Figure 4.12 shows the evolution of the relative water storage (WS_R) of the substrate throughout the study period, for all the test beds equipped with water content reflectometers.

During the periods between rainfall events, the test beds with substrate S2 (S1_L, S2_BS, and S2_M) present lower WS_R than the test beds with substrate S1. As described in section 4.1, S1 is more effective in retaining water than S2, which in turn presents a higher saturated hydraulic conductivity, meaning that it drains faster.

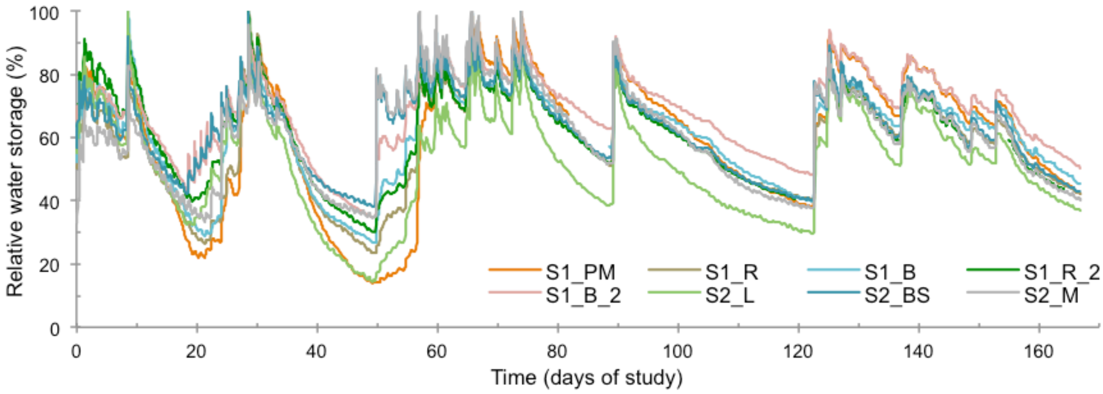


Figure 4.12 – Evolution of the relative water storage in the substrate in all the test beds throughout the study period.

For the same substrate, the vegetation covers can explain the different behaviour between test beds. S1_PM was covered with a mix of shrubs, grass and moss and the other treatments with the same substrate (S1_R and S1_B) had either shrubs (*Rosmarinus officinalis* L.) or grasses (*Brachypodium phoenicoides* (L.) Roem. &Schult) as vegetation covers. Figure 4.13 shows that S1_PM was always among the test beds with lower WS_R and that it many times took longer than the other treatments to achieve higher water content. This suggests that the combination of plants resulted in higher water extraction rates, which allowed to a more complete reset of the hydraulic properties of the substrate. It was also possible to observe on the chart that S1_R usually lost more water than S1_B, since the latter many times kept a WS_R higher than the other test beds, showing that shrubs extract more water than graminoids.

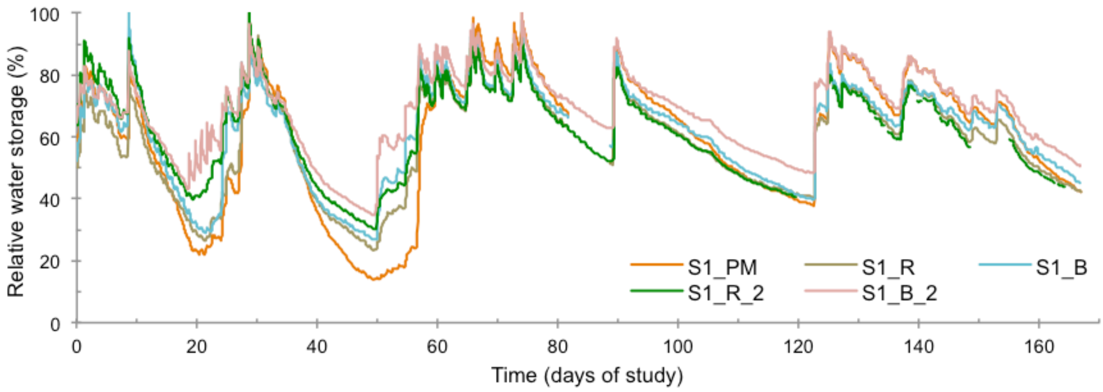


Figure 4.13 – Evolution of the relative water storage in the test beds with substrate S1 throughout the study period.

Results for substrate 2 are shown in Figure 4.14. S2_L is the test bed with lower water storage during the study period when compared to S2_M and S2_BS. This is clearly due to the water uptake by the shrubs. The test beds with moss (S2_M) and bare soil (S2_BS) show similar water storage behaviour. Despite the absence of vegetation, S2_BS sometimes lost more water than S2_M, which is probably related to the mosses capacity to store moisture.

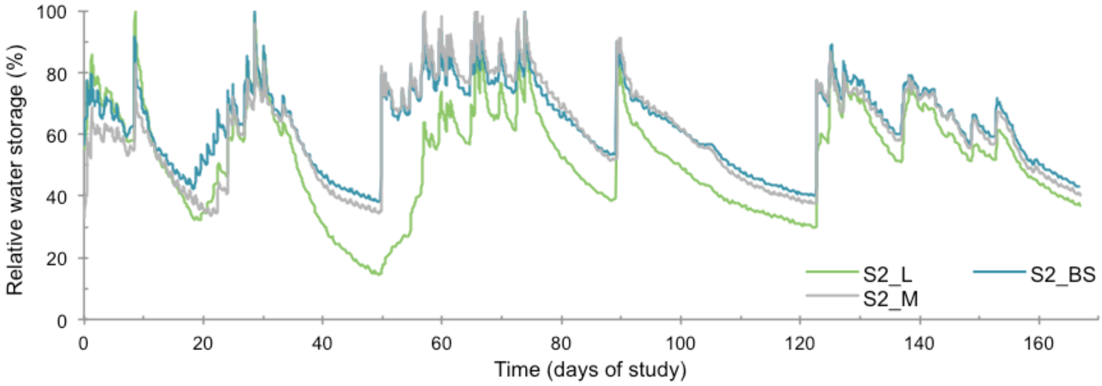


Figure 4.14 – Evolution of the relative water storage in test beds with substrate S2 throughout the study period.

As can be seen in Figure 4.12 the test bed with *Lavandula stoechas* subsp. *luisieri* (S2_L) was many times the one with lower WS_R. As described in section 4.1, substrate 2 had higher hydraulic conductivity, therefore a greater ease to loose water. This characteristic combined with the water uptake of a shrub resulted in great water loss, even surpassing the test bed treatment S1_PM.

4.4 Runoff

The runoff data was also collected from September 2014 to February 2015. The following results refer to the global analysis of the 414 events (46 rainfall events multiplied by 9 test beds) recorded during this period, not yet distinguishing the characteristics of the test beds.

Runoff did not occur in 147 of the 414 records – approximately 32 % of the events resulted in 100 % retention of the rainfall. Table 4.7 shows the basic statistics that allows to characterize the global runoff results.

Table 4.7 – Runoff events data summary

	D (h)	I_{RO} (mm h^{-1})	I_{ROa} (mm h^{-1})	d_{RO} (mm)
Maximum	154.73	21.90	0.96	89.06
Minimum	0.03	0.006	0.0004	0.003
Mean	35.22	4.48	0.22	10.79
Median	31.93	0.49	0.10	2.87
Standard Deviation	24.69	6.57	0.25	16.76

D – duration; I_{RO} – maximum intensity over 10 minutes; I_{ROa} – mean intensity; d_{RO} – depth;

The longest runoff event went on for 154.73 hours, the highest intensity registered was 21.90 mm h^{-1} and the largest amount of water drained in one event was 89.06 mm.

The boxplot and the histogram in Figure 4.15 illustrate de distribution of the runoff depths registered during the studied period.

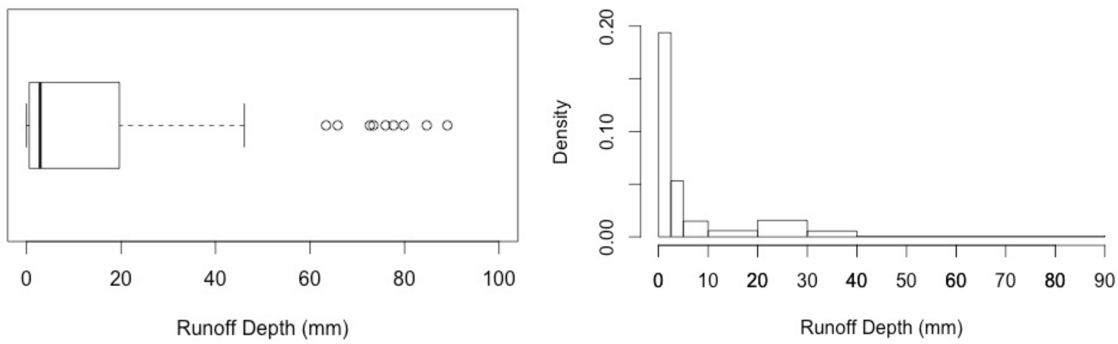


Figure 4.15 – Boxplot and histogram of the runoff depth.

Half of the events presented small depths (median = 2.87 mm), being the 0 to 2.5 mm class the most frequent. Despite the fact that the results were concentrated in an interval of small values, 25 % of the events were above 19 mm, with 13 runoff events classified as outliers, reaching values as high as 89 mm, as it is shown by the boxplot.

The duration of the runoff events varied between two minutes and 154.73 hours, prevailing values smaller than 50 hours. The boxplot and the histogram shown in Figure 4.16 illustrate the distribution of this parameter.

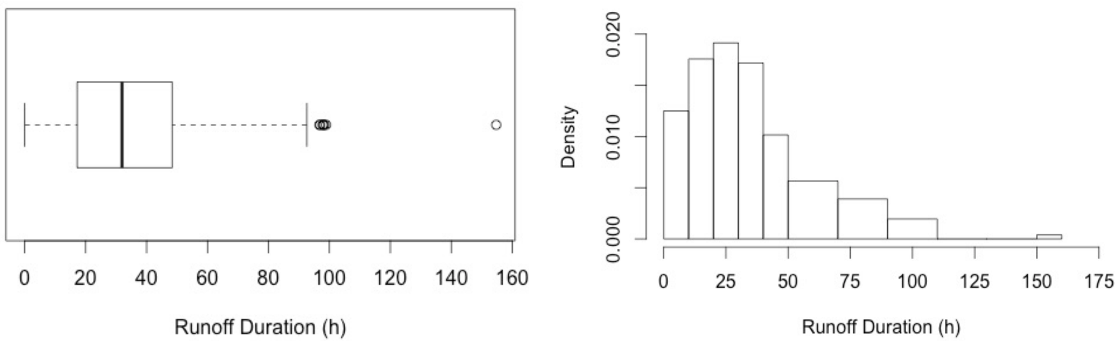


Figure 4.16 – Boxplot and histogram of the runoff duration.

Figure 4.17 shows the distribuition of the maximum runoff intensity values. Once again, the majority of the intensities were very small, with 50 % of the events not exceeding 0.49 mm h^{-1}. Despite that, the density increases again around 10 mm h^{-1}.

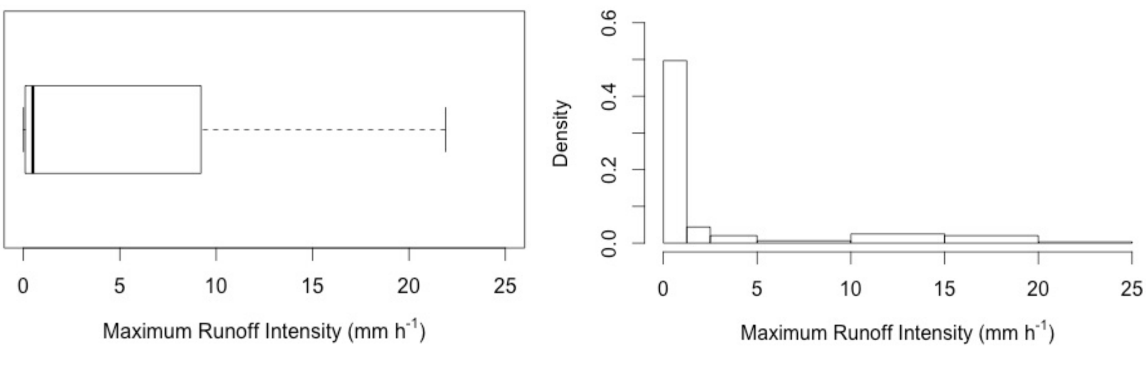


Figure 4.17 – Boxplot and histogram of the maximum runoff intensity over 10 minutes.

The runoff events can also be charaterized by their mean intensity, although this information has a limited interest because it is highly influenced by extreme values, as ocurred in the analysis of rainfall events. Figure 4.18 shows the distibution of the mean runoff intensity.

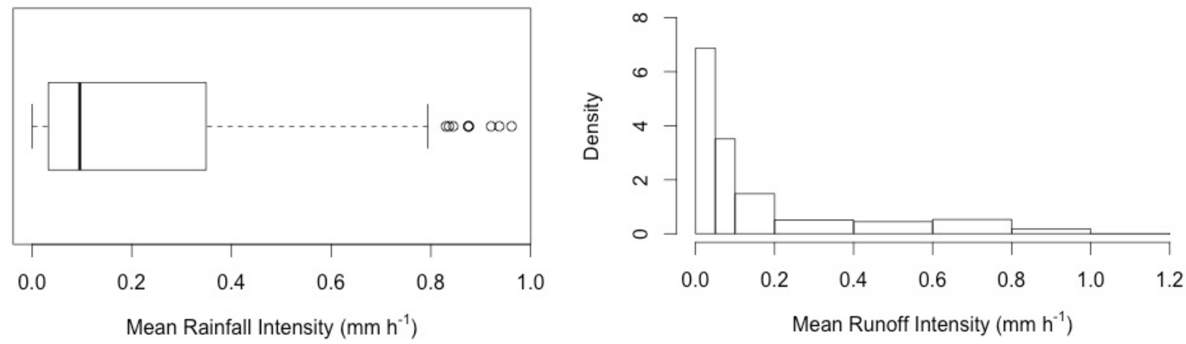


Figure 4.18 – Boxplot and histogram of the mean runoff intensity.

4.5 Rainfall - runoff relations

4.5.1 General analysis

The primary purpose of this study was to understand how green roofs, or, in this case, the test beds, can act as a barrier between the rainfall and the water reaching the drainage systems. Therefore, the characteristics of the runoff, when compared to the characteristics of the incoming rainfall, reflect that effect. To analyse the rainfall-runoff relations four variables were used: retention, runoff delay, rainfall peak attenuation and rainfall peak delay, which were calculated as described in section 3.4.5.

The hydrographs in Figure 4.19 and the cumulative hydrographs in Figure 4.20 illustrate the effect of the test beds, with a representative rainfall-runoff event for each rainfall class. The hydrographs clearly show the runoff delay, peak attenuation and peak delay, while the cumulative hydrographs are more illustrative of the retention effect.

Detailed data about each event is presented in Appendix 8.

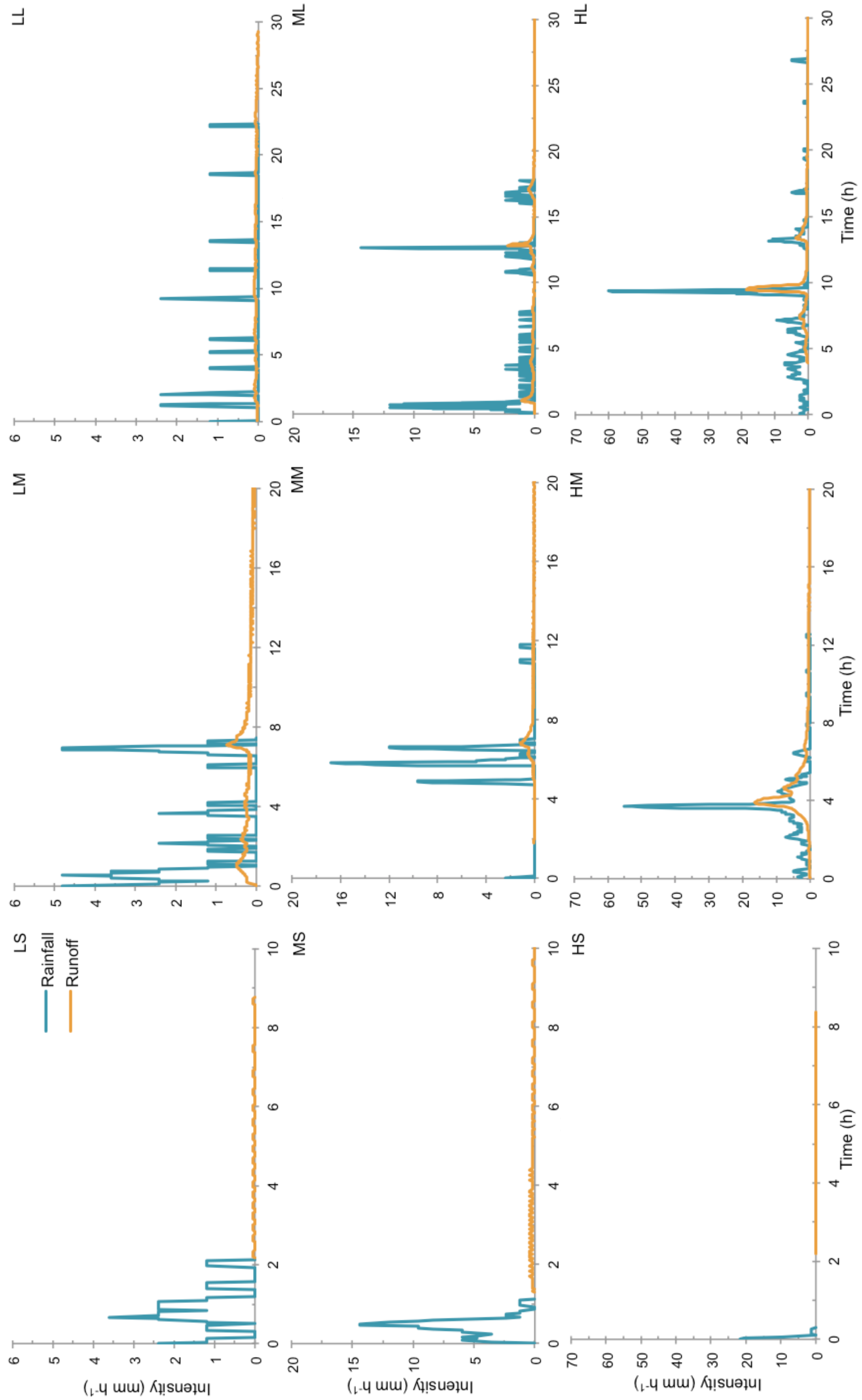


Figure 4.19 - Hydrographs of rainfall and respective produced runoff, for one event in each rainfall class.

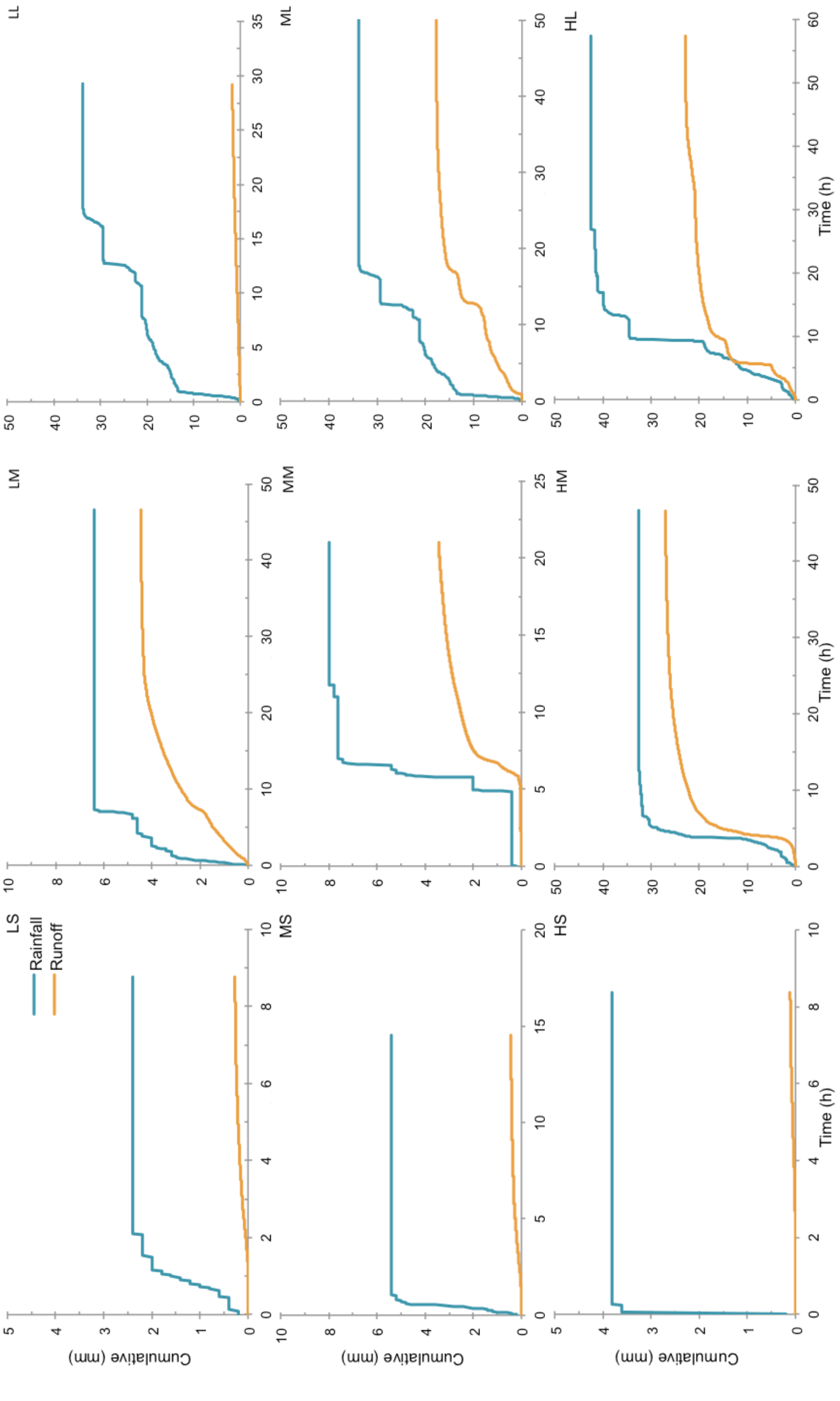


Figure 4.20 - Cumulative hydrographs of rainfall and respective produced runoff, for one event in each rainfall class.

4.5.1.1 Retention

The retention is the percentage of precipitation that is stored in the test bed, not contributing to runoff. In this section the retention will be analyzed as a whole, without any distinction between test beds.

Table 4.8 contains a summary of the basic statistics related to retention. In mean, the test beds were capable of retaining approximately 71 % of the rainfall. The maximum percentage retained was 100 % and the minimum was 5 %, meaning that in some events all the rainfall was retained while in others only a slight portion of it remained in the test bed, although it only occurred in a minority of the events.

Table 4.8 – Retention sample statistics summary

	Retention (%)
Maximum	100.00
Minimum	5.24
Mean	71.43
Median	83.90
Standard Deviation	30.15

Figure 4.21 shows the distribution of the retention values. The boxplot shows that only 25 % of the runoff events had retention lower than 41 % and in the histogram it is clearly visible that a lot of the events (44.2 %) had retention values between 95 and 100 %.

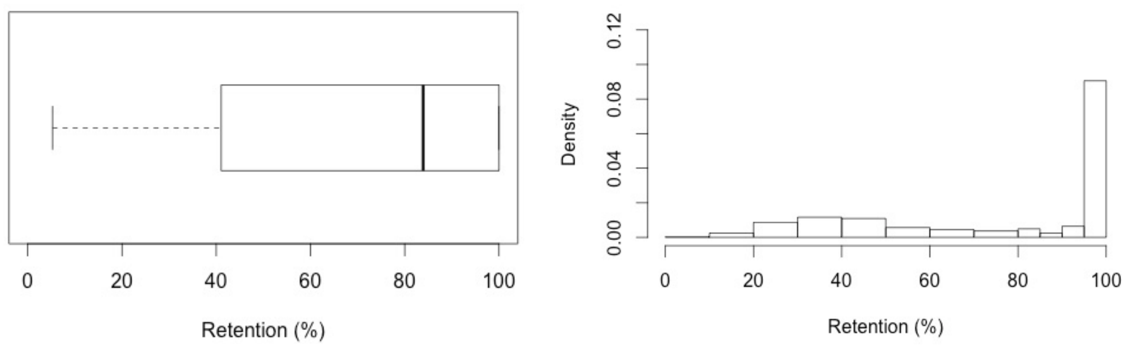


Figure 4.21 – Boxplot and histogram of the retention.

4.5.1.2 Runoff delay

The runoff delay, the time gap, in hours, between the start of the rainfall and the beginning of the runoff, was calculated for all the events in which runoff occurred. For the 147 rainfall events with 100 % retention, the runoff delay was considered infinite and was not included in the following statistical analyses. Table 4.9 contains statistical information about this variable, not distinguishing between test beds or rainfall events. The lowest values correspond to a simultaneous start of the rainfall and the runoff, which can be due to multiple factors that will be explored further ahead in this study. Figure 4.22 describes the distribution of the runoff delay data.

Table 4.9 – Runoff delay sample statistics summary

	Runoff Delay (h)
Maximum	35.17
Minimum	0.00
Mean	1.96
Median	0.40
Standard Deviation	3.82

Although the maximum runoff delay has been considerably high, 75 % of events resulted in delays shorter than 1.88 hours.

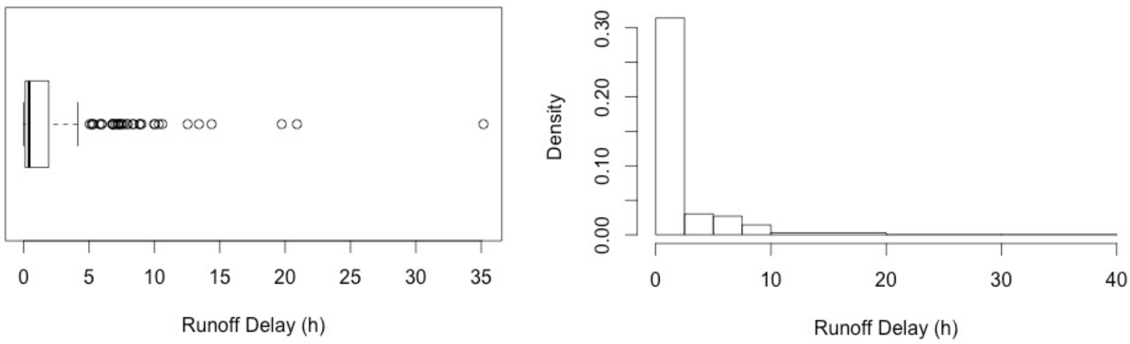


Figure 4.22 – Boxplot and histogram of the runoff delay.

4.5.1.3 Peak attenuation

The peak attenuation reveals, as a percentage, the capacity of the test beds to reduce the rainfall peak.

Table 4.10 shows general information on the statistics of the peak attenuation, not setting any differences between test beds or rainfall events.

Figure 4.23 illustrates the distribution of the data, showing that 50 % of the events registered peak attenuation above 98.46 % and 25 % of the events had more than 88.12 % peak attenuation.

Table 4.10 – Peak attenuation sample statistics summary

	Peak Attenuation (%)
Maximum	100.00
Minimum	29.55
Mean	90.59
Median	98.46
Standard Deviation	14.99

This parameter is characterized by a great asymmetry and variability of results, as it is expressed by the boxplot, including many outlier values.

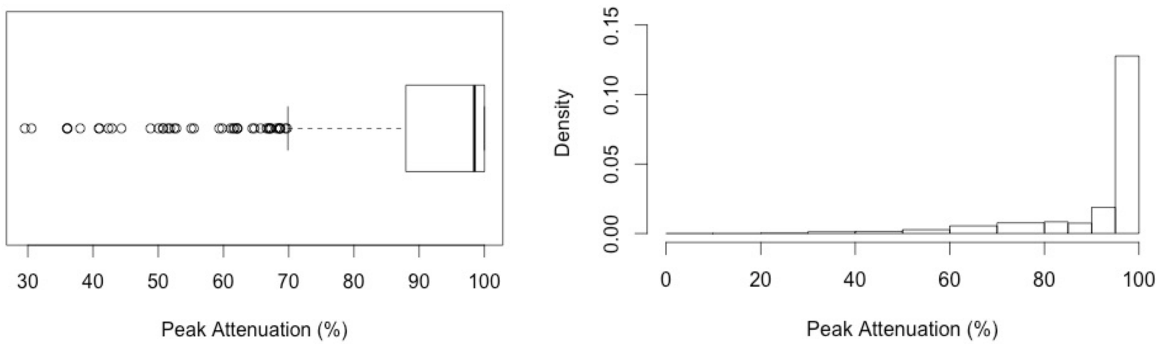


Figure 4.23 – Boxplot and histogram of the peak attenuation.

4.5.1.4 Peak delay

Peak delay is the difference, measured in hours, between the peak of the rainfall and the peak of the runoff.

As described for the runoff delay (section 4.4.1), the 147 events with 100 % rainfall retention were considered to have infinite pick delay and were not included in the following statistical analysis.

Table 4.11 shows the main statistical information about this parameter. The minimum value recorded was zero, corresponding to event at which the runoff peak coincided, in time, with the rainfall peak.

The boxplot and the histogram in Figure 4.24 show the distribution of the values related to this parameter. The histogram reveals that most of the values are in the 0 to 2.5 hours category.

Table 4.11 – Peak delay sample statistics summary

	Peak Delay (h)
Maximum	35.17
Minimum	0.00
Mean	1.60
Median	0.40
Standard Deviation	3.75

Although most of the results were quite low (the median was 0.40 hours), their range was wide, reaching more than 35 hours of delay.

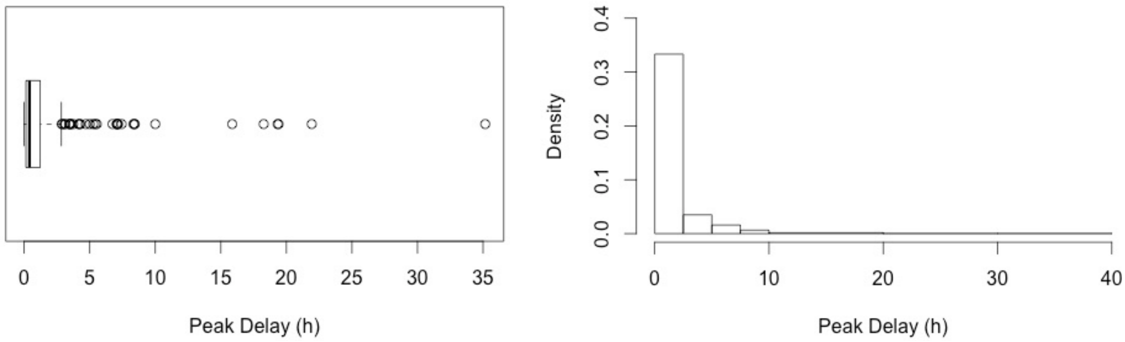


Figure 4.24 – Boxplot and histogram of the peak delay.

The test beds are expected to have a role in the delay of the rainfall peak, which would translate, in a full scale situation, in the relief of the pressure upon the urban drainage systems (GRO 2014).

The global retention results obtained in the present study (71.43 %) belong to the same range of values reported in other studies: in Hutchinson *et al.* (2003) the global average retention was 69 %, in Liu and Minor (2005) it was 57 %, in Fioretti *et al.* (2010) it was 68 %, in Voyde *et al.* (2010) 78 % and in Beecham *et al.* (2012) it was 69 %.

The runoff delay here recorded was, in mean (1.96 h), higher than the one reported by Liu and Minor (2005) - 20 to 40 minutes - but lower than ones from the study of Palla *et al.* (2010) (5.17 h).

The peak attenuation mean value (90.59 %) is also in agreement with other studies, for example, the study of Fioretti *et al.* (2010), in which the authors report a global mean peak attenuation of 89 %. Also Voyde *et al.* (2010) have achieved peak attenuations of 91 %, in average. On the other hand, Liu and Minor (2005) had lower results, not exceeding 60 % peak attenuation.

4.5.2 Treatment analysis

This section intends to analyse the obtained results by comparing the response of the different test bed treatments, as opposed to the previously made overall analysis. At first, in section 4.5.2.1, the goal is to determine whether the rainfall characteristics had any effect on the runoff response of each treatment. After that, in section 4.5.2.2, the test bed treatments are compared in order to verify the differences between substrates and vegetation covers, so a best performing combination can be found. When there was more than one test bed with the same treatment (combination of substrate type and vegetation cover), they were combined and the resulting mean was used as representative for further calculations.

The six treatments were the following:

S1_PM – substrate 1 and a mix of shrubs and grasses (*Rosmarinus officinalis* L., *Lavandula stoechas* subsp. *luisieri* L. and *Brachypodium phoenicoides* (L.) Roem. &Schult.) and moss;

S1_R – substrate 1 and *Rosmarinus officinalis* L.;

S1_B – substrate 1 and *Brachypodium phoenicoides* (L.) Roem. &Schult.);

S2_L – substrate 2 and *Lavandula stoechas* subsp. *luisieri* L.;

S2_M – substrate 2 and mosses;

S2_BS – substrate 2 without vegetation (bare soil).

4.5.2.1 Effect of rainfall characteristics in the runoff response

After grouping the rainfall events by classes, the four variables (retention, runoff delay, peak attenuation and peak delay) were used to analyse the rainfall-runoff relations for each test bed treatment. This section aims to characterize the treatments response to the different rainfall classes. The first indicator of a treatment's capacity to mitigate rainfall effects is the number of times it performed total retention, relatively to the 46 recorded rainfall events, which is shown in Figure 4.25. All the test beds had 100 % retention in events belonging to the LS, LM and MM classes and none had it in the HM and HL classes. S1_PM was the treatment with a larger amount of total retentions, distributed by more rainfall classes. For example, it was the only test bed to perform full retention on events in the ML class. The charts of S1_R and S2_L are very similar, both showing more 100 % retention situations than S1_B. S2_M and S2_BS were clearly the treatments with the least capacity to achieve the 100 % retention and, contrary to what was expected, for S2_M this happened less times than in S2_BS in rainfall classes LM, MM and HS. Appendix 9 contains extended information on the events without runoff.

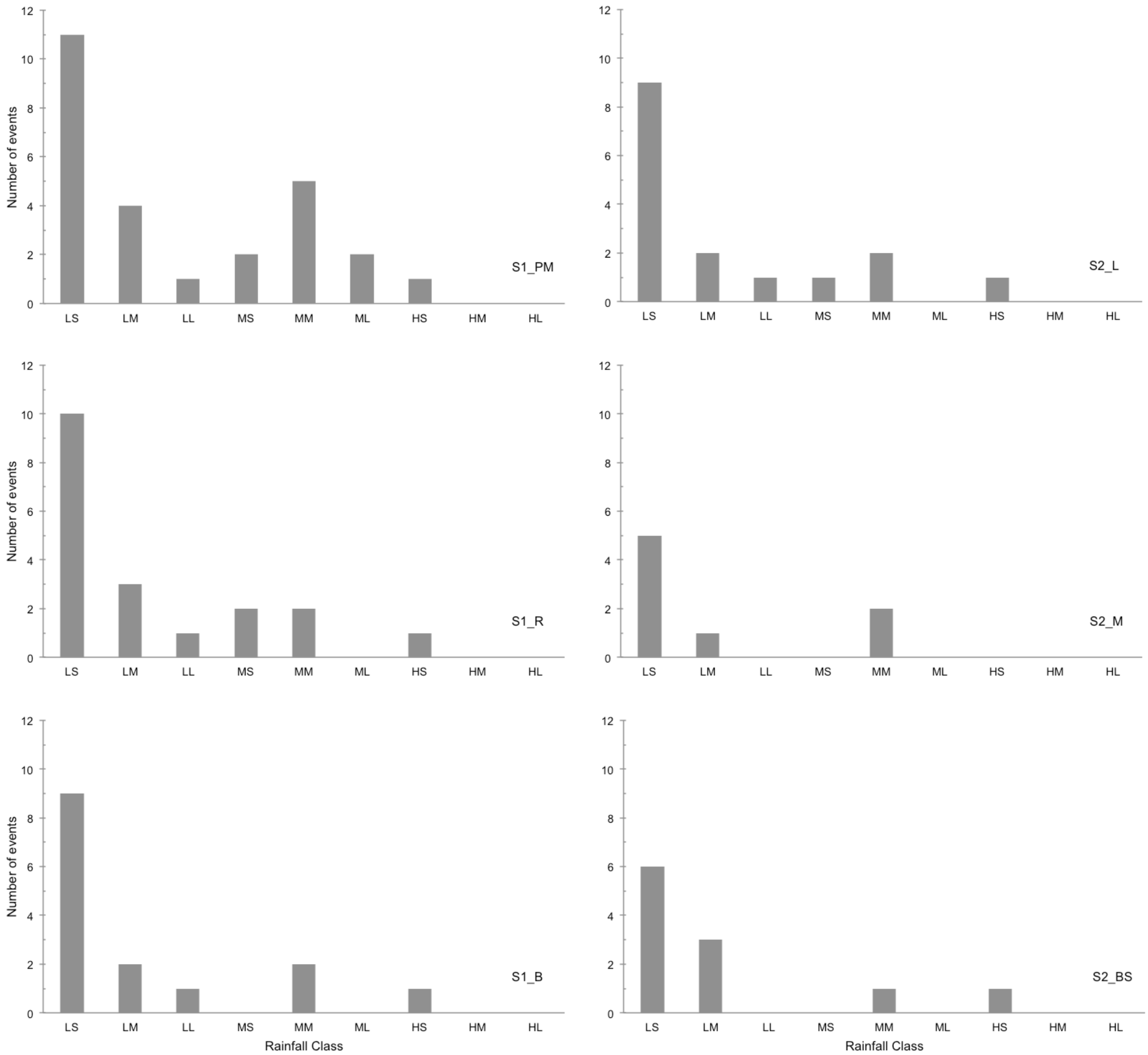


Figure 4.25 - Number of events that did not produce runoff by rainfall class, for each treatment.

For the analysis of the rainfall-runoff variables, the goal was to compare the estimates of the mean value and the 95 % confidence interval for the mean, between the different rainfall classes and to analyse possible causes for the variability of the results (evaluated by the amplitude of the confidence intervals). The rainfall classes LL, HS and HM did not have enough observations (events) for the calculation of the confidence interval, therefore, only the sample means are presented.

The charts only show physically possible values: values between 0 and 100 % for retention and peak attenuation and values equal or above zero for runoff and peak delay. Therefore, confidence intervals were truncated whenever necessary.

4.5.2.1.1 Retention

Figure 4.26 shows the estimate and the 95 % confidence interval for the mean retention for the studied period, by rainfall class and for the three test beds with substrate 1. For events with maximum rainfall intensity lower than 5 mm h^{-1} and duration less than 3 h (LS), all the treatments have shown a sample mean retention close to 100 %. For the same maximum intensity but longer durations (D > 3 h) (LM), the sample mean retention decreased to less than 70 %, except for S1_PM that kept retaining close to 90 % of the rainfall. For the other intensity classes (Medium and High) the trend was the same as the duration increased. The rainfall class HM was an exception, presenting a very low retention, which might have been related to the high relative water storage (87 %) in the beginning of the only rainfall event in this class.

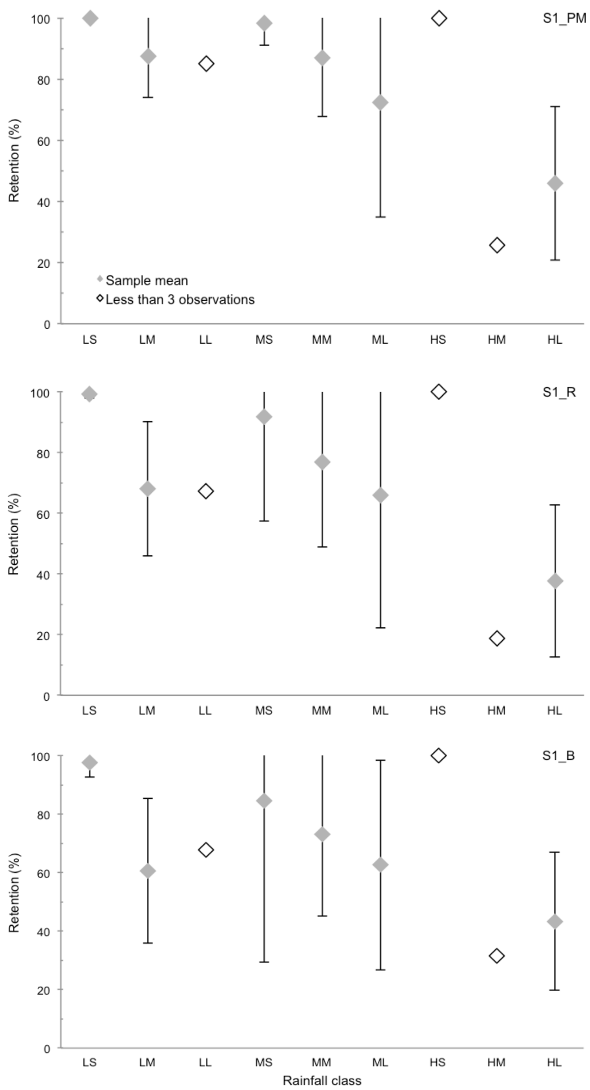


Figure 4.26 – Mean retention (estimate and 95 % confidence interval) for the studied period by rainfall class and for all the test bed treatments with Substrate 1.

For the three treatments in Figure 4.26, sample mean retention was higher than 50 % for all classes except for HM and HL, meaning that for events with maximum intensities above 20 mm h^{-1} and durations longer that 3 h, only 50 % or less of the rainfall was retained, in mean. S1_PM had a sample mean retention higher than 75 % for all the rainfall classes, except for ML, HM and HL. S1_R and S1_B only retained 75 % or more for rainfall classes of short duration events (D < 3 h) and for MM, in which the treatment S1_R retained in mean 76.81 % of the rainfall.

Total retention occurred 26, 19 and 15 times on S1_PM, S1_R and S1_B, respectively (Figure 4.22). Low maximum intensity and short duration events resulted in the highest percentage retentions for the three test bed treatments.

The highest rainfall maximum intensity, for which 100 % retention was achieved, for all the three treatments, was 21.6 mm h^{-1}, in an event with 0.27 h of duration, which occurred in September 2014. The second highest maximum intensity with 100 % retention was 16.8 mm h^{-1} for S1_PM and S1_R and 14.4 mm h^{-1} for S1_B.

Figure 4.27 shows the same kind of results regarding the treatments with substrate 2 (S2_L, S2_M and S2_BS). In the rainfall class LS the mean retention was also high. As in the previous case (substrate 1), for the same maximum rainfall intensity, the retention decreased as the duration increased, except for the HM class.

With the exception of classes HM and HL, all the classes had sample retention means above 50 % on S2_L and S2_M. For S2_BS, and besides HM and HL, also LL presented a value just below this limit (46.38 %).

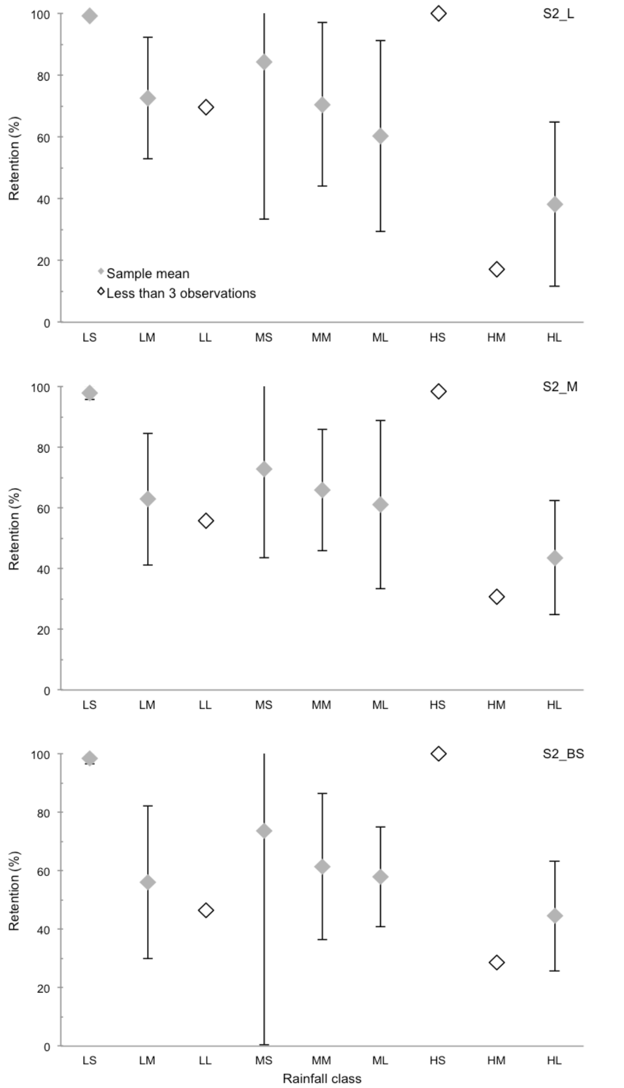


Figure 4.27– Mean retention (estimate and 95 % confidence interval) for the studied period by rainfall class and for all the test bed treatments with Substrate 2.

S2_L was the only test bed in this group retaining more than 75 % in all the short duration classes (LS, MS, HS), as had also been observed for all the test beds containing substrate 1. For the other two test beds this only occurred in the classes LS and HS.

Despite that the retention results were slightly lower than the ones from substrate 1, there still were some events with 100 % retention: 15 for S2_L, 7 for S2_M and 9 for S2_BS, in events distributed by the classes LS, LM, LL, MS, MM and HS. For S2_L, the event with the highest maximum rainfall intensity for which the retention was 100 % had 21.6 mm h^{-1}, as for all the S1 treatments. For S2_M and S2_BS this limit was much lower - the maximum intensity was 4.8 mm h^{-1}.

For both substrates, the highest variability (widest amplitude of the confidence interval) occurred in classes MS, ML and HL and the lowest in class LS, as shown in Figures 4.26 and 4.27 (LL, HS and HM did not have enough observations). The low confidence interval value in the LS class is due to the high retention in all the events, a consequence of the characteristics of the rainfall events in this class. As can be seen from the charts in Figure 4.28, the variability associated with the percentage retention values, probably reflects different substrate water storage at the beginning of the different events, leading to distinct retention capacities independent of the rainfall characteristics. It was generally noticeable that lower WS_R corresponded to higher retention and higher WS_R resulted in lower retention, giving support for the thesis stated above about the influence of the WS_R in the response of the test bed treatment, for similar rainfall characteristics.

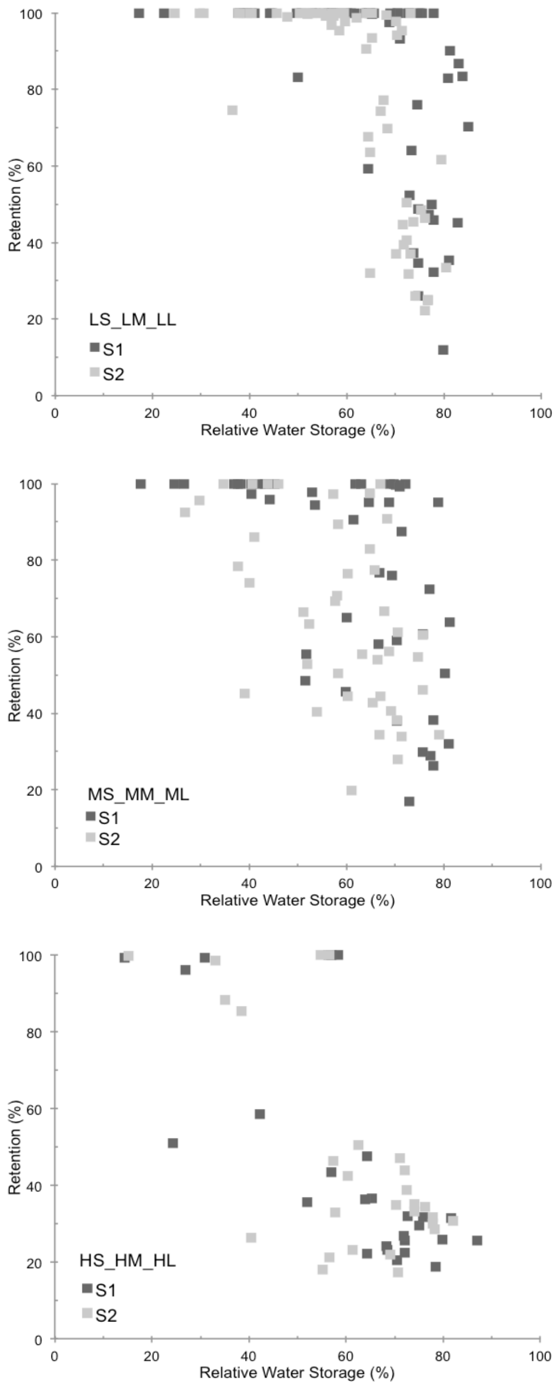


Figure 4.28 – Relation between retention and relative water storage in the substrate at the beginning of the rainfall by groups of maximum rainfall intensity.

In the classes with Low maximum rainfall intensity, for test beds containing substrate 1, there was 100 % retention for higher WS_R than for test beds with S2. The limit WS_R for 100 % retention was 77.9 % for S1 and 73.2 % for S2. For the latter, the retention values tended to decrease more for lower WS_R than for S1. There were retention values over 80% corresponding to WS_R as high as 83.9 % for treatments with S1, while for treatments with S2, there was retention above 80 % only for WS_R values below 73.2 %. This implies a difference larger than 10 %.

Considering a limit of 50 % retention, the test beds containing S1 performed better than the others, registering retention values above 50 % for WS_R as high as 85 %, contrary to test beds with S2, for which retention on this range of values only occurred when the WS_R did not exceed 70 %.

Regarding the classes MS, MM and ML, the maximum WS_R for which 100 % retention occurred was 72.2 % and 66.9 % for S1 and S2 treatments, respectively.

The contrast is even bigger if we consider a retention limit of 80%. This occurred for test beds with S1 until WS_R was 78.8 % and for test beds with S2 until WS_R was 68.4 %. As for the previous class, this difference is higher than 10 %.

The trend is the same for retentions above 50 %. The S1 group exceeded 50 % retention with WS_R as high as 81.3 %, while for the S2 group the limit was 75.7 %.

In the classes with High maximum rainfall intensity there was clearly a higher concentration of retention results below 50 % than in the other classes. Still, there were some retentions of 100 %, which, once more, corresponded to higher WS_R values for treatments containing S1 than for the ones containing S2. In most of the events included in the high maximum intensity rainfall classes, the initial relative water storage in the substrate does not seem to dictate the test beds response concerning the retention. Due to the size of the rainfall events, mainly in the HL class, the amount of water received by the test beds is so high that the conditions in the beginning of the rainfall loose relevance.

4.5.2.1.2 Runoff delay

The runoff delay, as well as the peak delay, which is presented in section 4.5.2.1.4, is not measurable when the retention is 100 %. In those occasions, these variables were considered infinite. As this situation varied between treatments, to analyse runoff and peak delay, only the events in which at least 4 treatments had produced runoff were considered for comparison. For the other one or two test beds without runoff on the selected event, the rainfall class to which that event belonged was excluded from the analysis. More information about the number of events without runoff is available in Figure 4.25 in section 4.5.2.1 and in Appendix 9.

Figure 4.29 illustrates the estimated mean values and the 95 % confidence intervals for the mean runoff delay for the treatments with substrate 1 (S1_PM, S1_R and S1_B) and for each rainfall class.

S1_PM was the treatment with more 100 % retention cases, therefore not having many classes under analysis. In the HL class it was the treatment with the highest runoff delay estimate mean.

Figure 2.20 presents the same data regarding the treatments with substrate 2. For S1_R, S1_B and S2_L, the classes MM and ML presented high variability. As these include rainfall events with intermediate characteristics, the response was diverse.

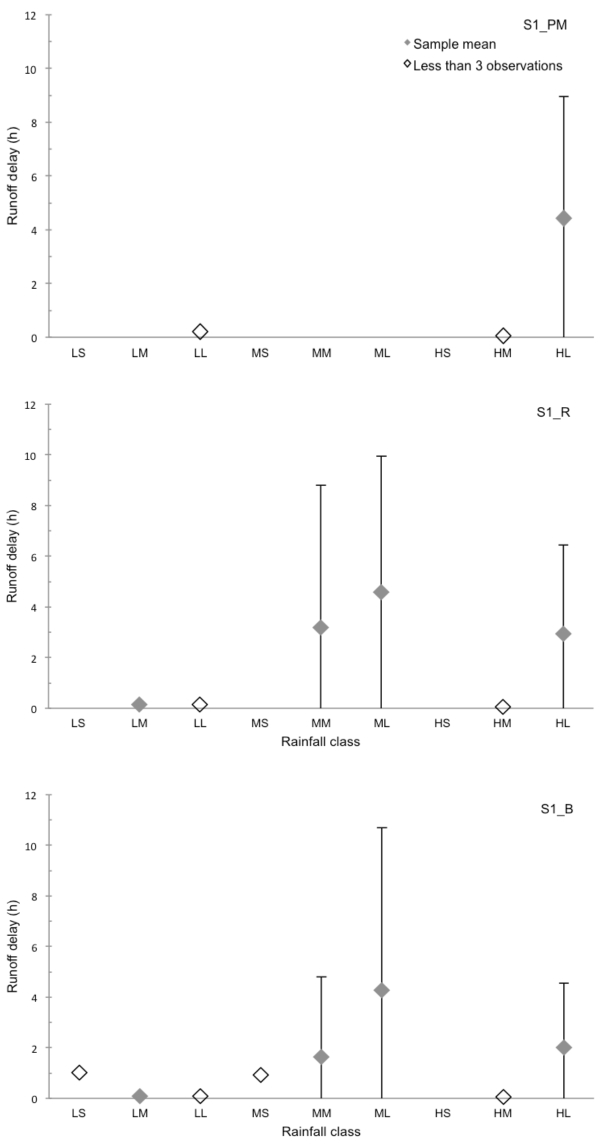


Figure 4.29 – Mean runoff delay (estimate and 95 % confidence interval) for the studied period by rainfall class and for all the test bed treatments with Substrate 1.

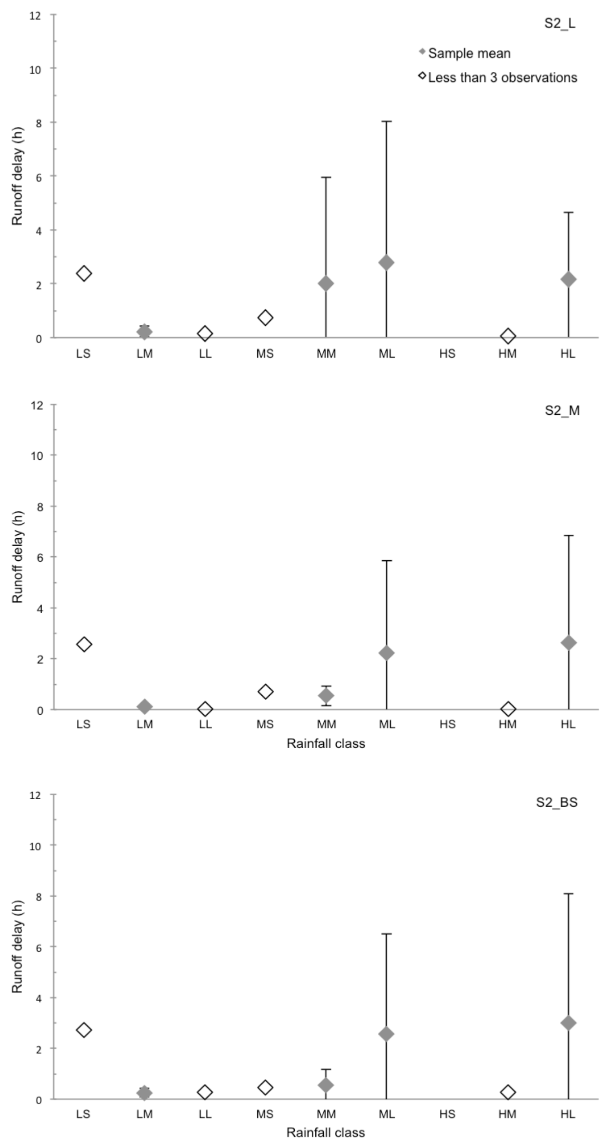


Figure 4.30 – Mean runoff delay (estimate and 95 % confidence interval) the studied period by rainfall class and for all the test bed treatments with Substrate 2

S2_M and S2_BS showed much lower sample means and narrower confidence intervals in those classes, mainly in MM, revealing a consistently worse performance. For S1_R, S1_B and S2_L the highest runoff delay values occurred in ML. For S2_L and S1_B, that was the only class with a sample mean superior to 2.5 h. S1_R surpassed this limit in classes MM, ML and HL.

Many times, higher runoff delay sample means were associated with the long or medium duration rainfall classes. This was probably a consequence of what was considered a rainfall event (see section 3.2) and with the way the data was analysed: many times, long events resulted from the combination of two or more short events because the runoff was not interrupted. Therefore, these long events might have started with low intensity rainfall, allowing for long runoff delays, but were followed by high intensity rainfall, which positioned them in the HM or HL class.

Despite the runoff delay results here analysed, the charts in Figure 4.25 show which treatments performed better, based on the number of events without runoff.

To try to explain the variability of results within the same rainfall class of maximum intensity and duration, runoff delay values were related to the relative water storage (WS_R) conditions of the substrate at the beginning of the rainfall events (Figure 4.31).

Regarding the classes with Low maximum rainfall intensity, S1 had a maximum WS_R of 85 %, which corresponded to a runoff delay of 0.2 h, while S2 had a maximum WS_R of 80 % that only allowed a runoff delay of 0.13 h. In these classes the lower runoff delay values occurred for WS_R above 60 % for S2 and only above 74 % for S1, there being an overall concentration of runoff delay values under 0.5 hours associated with WS_R values between 65 and 80 %. The relation of the WS_R with the runoff delay is less evident than it was with the retention: it only seemed to be relevant when the WS_R was between 45 % and 80 % for S2 and between 65 % and 80 % for S1. The events with a longer runoff delay were not the ones with lower WS_R.

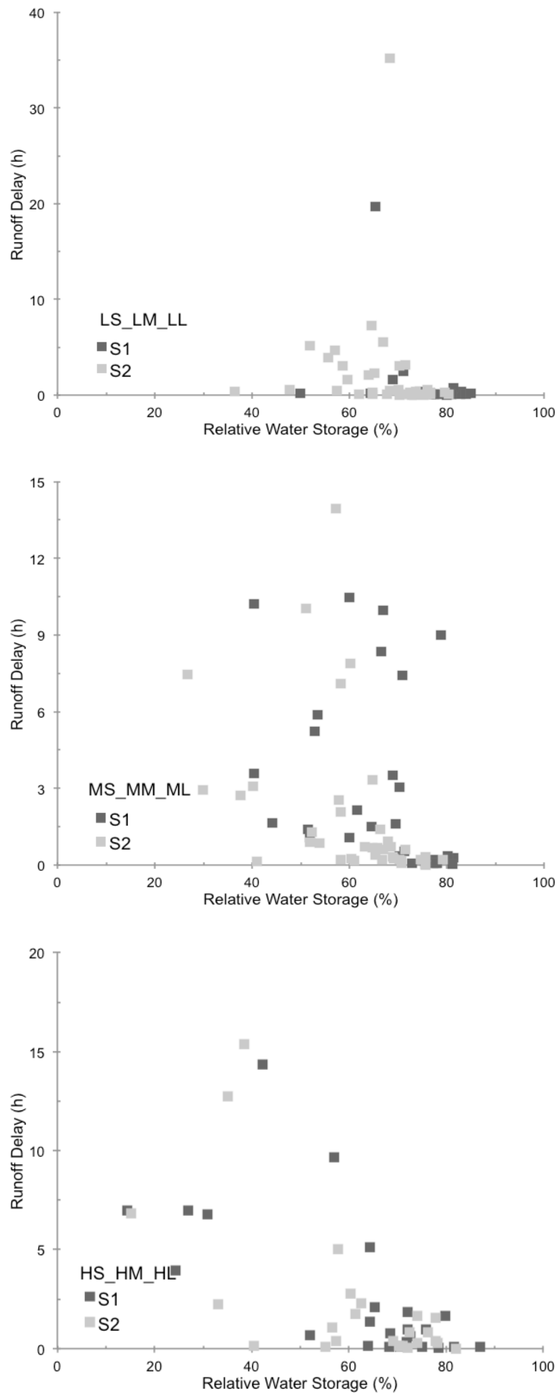


Figure 4.31 – Relation between runoff delay and relative water storage in the substrate at the beginning of the rainfall by groups of maximum rainfall intensity.

In the classes with Medium maximum rainfall intensity the longer runoff delay also did not correspond to the lower WS_R: runoff delays superior to 6 hours occurred associated to a wide range of WS_R values (20 % to 80 %). However, there was a concentration of low runoff delay values (shorter than 1 h) in correspondence with WS_R from 65 % to 80 %. In these classes, the observable difference between the substrates was that S1 reached runoff delay values higher than S2 for high WS_R.

In the High maximum rainfall intensity class (HS, HM and HL) there seemed to be a stronger relation between the two variables. Long runoff delays (more than 6 h) did not happen for WS_R higher than 57 % and delays shorter than 2 h were concentrated between 60 % and 90 % WS_R.

For the runoff delay, the relation with the substrate's water content displayed a growth tendency from the rainfall class of Low maximum intensity to the ones of High maximum rainfall intensity.

4.5.2.1.3 Peak attenuation

Peak attenuation had much less variability of results (narrow confidence interval for the mean) than the retention parameter, since the attenuation of the rainfall peak was very close to 100 % for several events.

Among the group of test beds with substrate 1 (Figure 4.32), S1_PM and S1_R performed better. In these treatments, sample peak attenuation means below 95 % only occurred in 3 rainfall classes: ML, HM and HL. For S1_B sample peak attenuation means below 95 % occurred in rainfall classes MS, ML, HM and HL, showing a worst capacity to delay the rainfall peak than the other two treatments in substrate 1.

For S1_PM the highest attenuation sample mean (100 %) corresponded to the LS and HS classes. Although test beds S1_R and S1_B achieved attenuation values close to 100 % in many rainfall classes, total attenuation happened only for HS. The lowest values stand out more, having occurred in rainfall class HM for the three test beds, with 66.9 %, 66.85 % and 73.62 % for S1_PM, S1_R and S1_B respectively.

Figure 4.33 shows the estimate mean and the approximate 95 % confidence interval for the mean, regarding the peak attenuation in test beds with substrate 2.

For the peak attenuation, the differences between the treatments with substrate 1 and the ones with substrate 2 were not as evident as for other variables. As for the previous group, the treatments with substrate 2 had the lowest peak attenuations in rainfall classes ML, HM and HL.

S2_L only had sample mean peak attenuation under 95 % in classes ML, HM and HL. S2_M had it in MM, besides those three, and S2_BS performed under 90 % in rainfall classes MS, MM, ML, HM and HL.

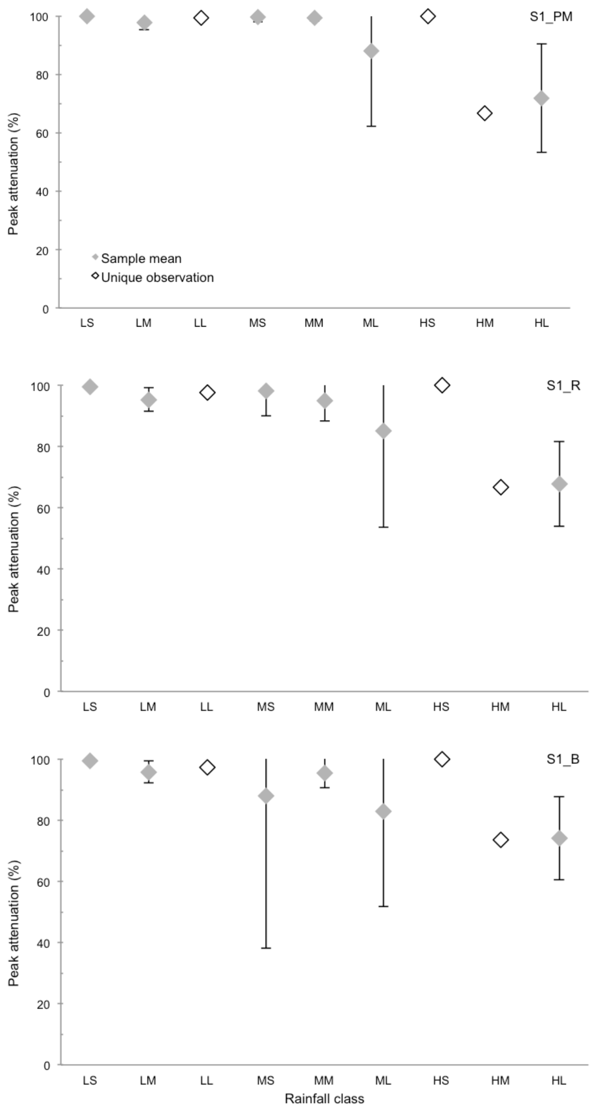


Figure 4.32 – Mean peak attenuation (estimate and 95 % confidence interval) for the studied period by rainfall class and for all the test bed treatments with Substrate 1.

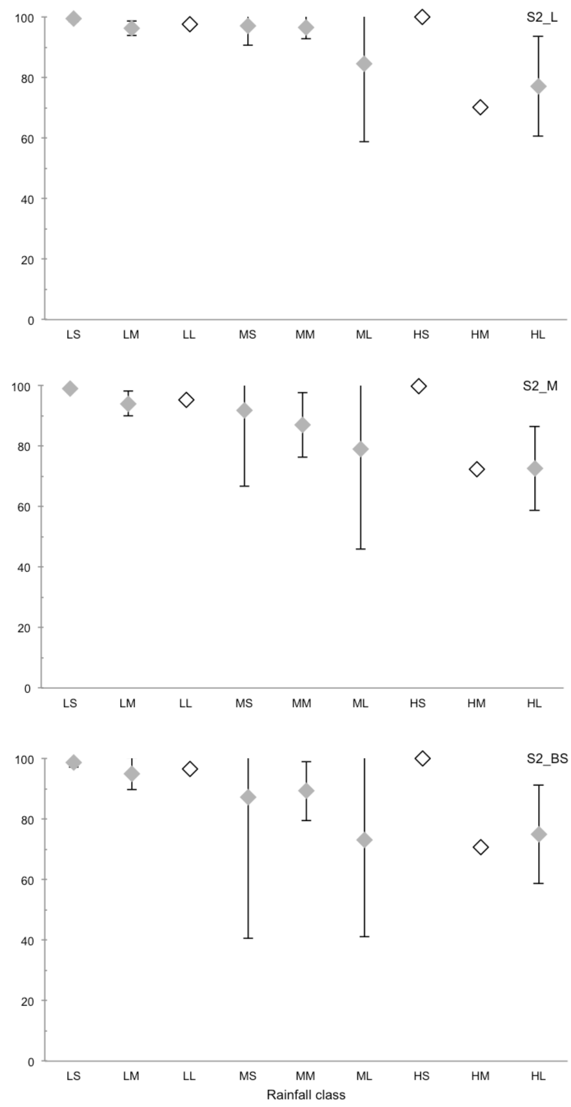


Figure 4.33 – Mean peak attenuation (estimate and 95 % confidence interval) for the studied period by rainfall class and for all the test bed treatments with Substrate 2.

This last test bed produced the lowest overall sample mean – 87.30 % (mean of all classes means) but S2_M had a similar performance, with an overall sample mean of 87.70 %. S2_L had an overall mean of 91.09 %, which was more similar the ones of the test beds with substrate 1: S1_PM had 91.62 %, S1_R 89.52 % and S1_B 89.65 %.

Despite the small variability in this parameter, there was a decreasing trend from the LS to the HL class. All the treatments performed worse for HM and HL rainfall events and they all performed better for LS, LM and LL. In the intermediate classes (MS, MM and ML) it is possible to notice that the peak attenuation capacity tends to diminish as the rainfall duration decreases. Between the three test bed treatments containing substrate 2, S2_L was the one with less variability. S2_M and S2_BS had very similar sample means, but the latter showed higher variability.

Following the same reasoning as for the previous studied variables, in the charts in Figure 4.34, the measured peak attenuation values were compared to the relative water storage in the substrate at the beginning of the rainfall event (WS_R), in an attempt to explain why the variability was sometimes considerable, within each rainfall class.

Regarding the group of rainfall classes with Low maximum intensity there seemed to be a relation between peak attenuation and WS_R, with peak attenuation decreasing as WS_R increased, but only from 65 % WS_R ahead. As observed in other rainfall – runoff relation variables, substrate 1 was able to keep higher peak attenuation values for larger WS_R values than substrate 2.

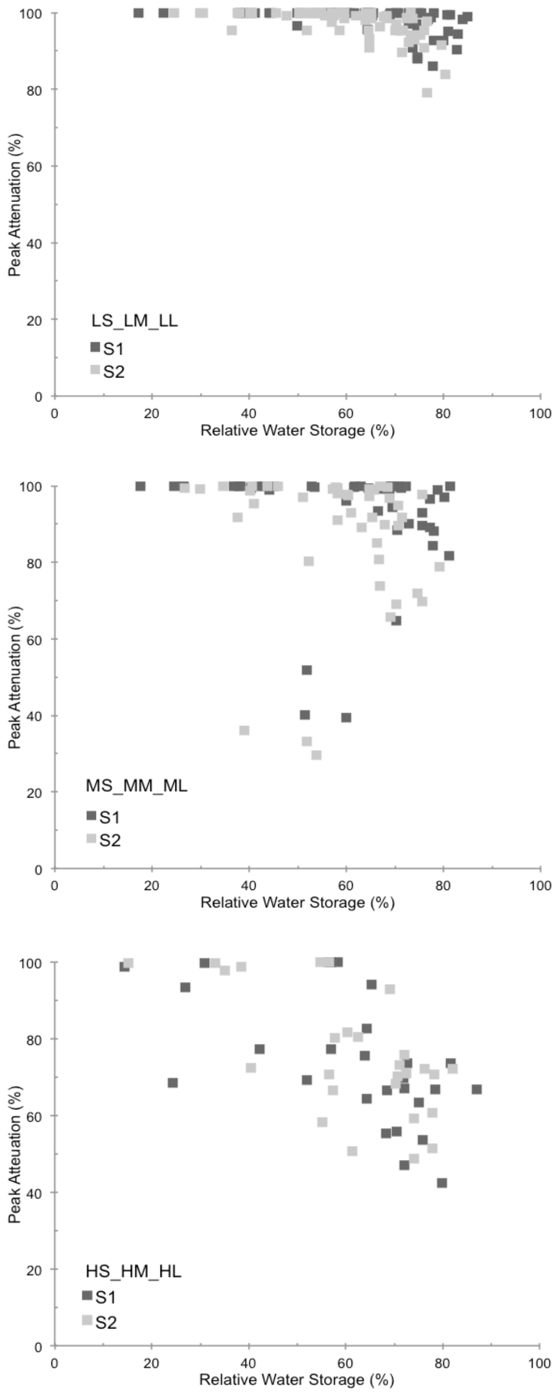


Figure 4.34 – Relation between peak attenuation and relative water storage in the substrate at the beginning of the rainfall by groups of maximum rainfall intensity.

In the group of rainfall classes with Medium maximum intensity, peak attenuations lower than 90 % only happened for WS_R values above 36 % and most of the attenuations of 95 % or more were associated with WS_R values higher than 55 %. It is also noticeable that for WS_R higher than 60 %, the peak attenuation response tended to decrease.

For the last group of classes, HS, HM and HL, the relation between the two variables was much more pronounced, although the differences between the substrates were less evident. For WS_R values above 60 % there were no total peak attenuations (100 %) and peak attenuation under 85 % is concentrated in the second half of the WS_R axis, which corresponds to relative water storage higher than 50 %.

4.5.2.1.4 Peak delay

The analysis of the peak delay done in this study was similar to the one made for the runoff delay and described in section 4.5.2.1.2

Figures 4.35 and 4.36 show the estimates and the 95 % confidence interval for the mean of the peak delay, for the rainfall classes in which the calculations were possible, for test beds with substrate 1 and substrate 2, respectively.

For S1_PM, the rainfall class HL was the only one in which it did not accomplish 100 % retention in any event (more information in Figure 4.25, section 4.5.2.1 and in Appendix 9), allowing to calculate the sample mean and the 95 % confidence interval for the mean. In that class, S1_PM showed very low variability, since the results only varied between 0.07 and 0.73 h.

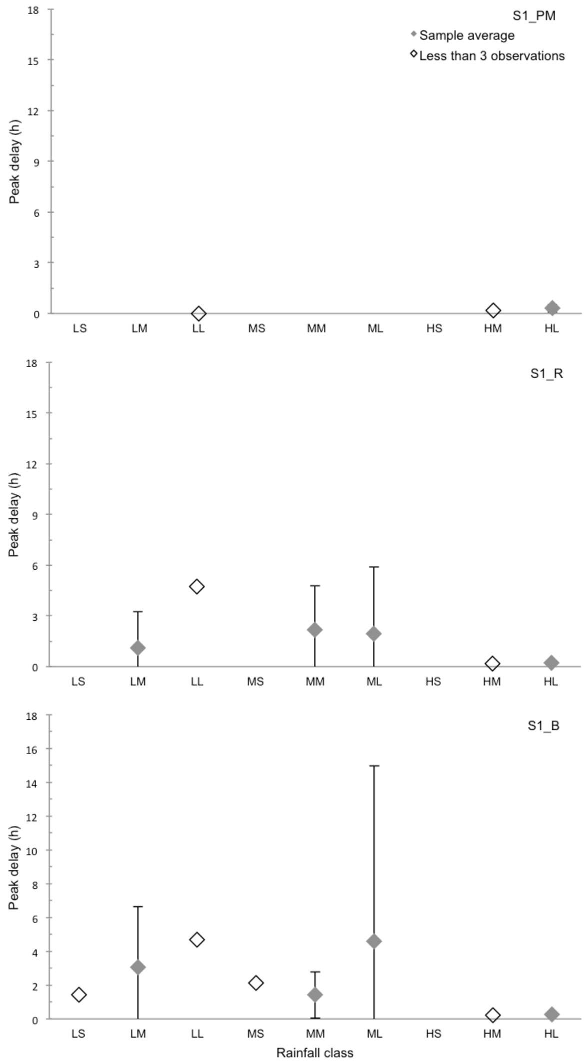


Figure 4.35 – Mean peak delay (estimate and 95 % confidence interval) for the studied period by rainfall class and for all the test bed treatments with Substrate 1.

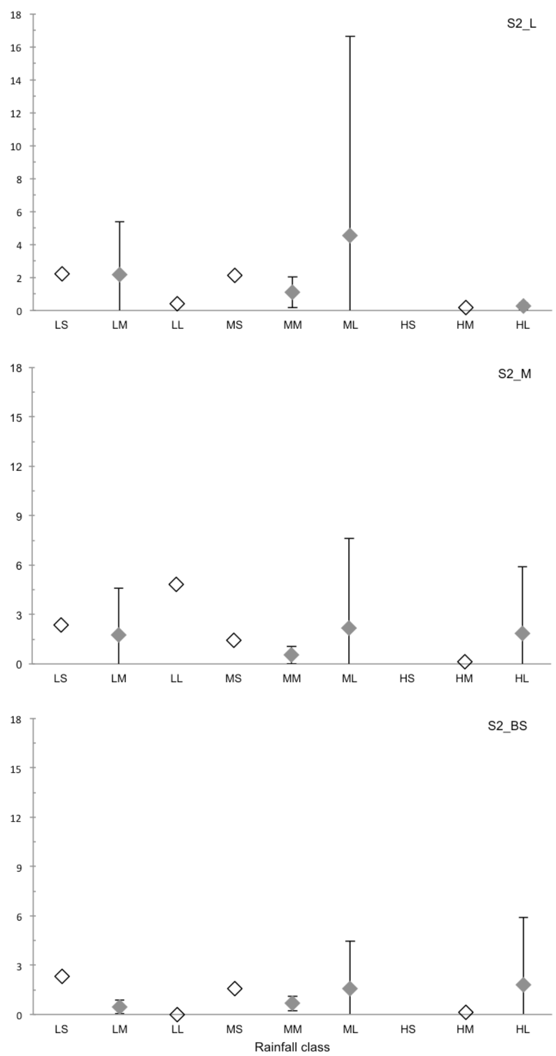


Figure 4.36 – Mean peak delay (estimate and 95 % confidence interval) for the studied period by rainfall class and for all the test bed treatments with Substrate 2.

The variation in peak delay between rainfall classes was not regular, as they were for the other variables, as they did not decrease with the increase in maximum intensity or duration.

For example, in S1_B, the peak delay sample mean was longer in LL than in LM and LS and longer in ML than in MS, contrary to what would be expected.

Among the group with substrate 2, S2_L was the test bed with more classes with sample peak delay means above 2 hours – LS, LM, MS and ML; S2_M had 3 classes in these conditions (LS, LL, ML) and S2_BS had only one (LS). For S2_BS the sample mean peak delay decreased with the increasing of duration between the classes with Low maximum intensity, but this was the only case in which this relation was verified.

Unexpectedly, S2_M and S2_BS had higher peak delay sample means in the HL class than all the other treatments. This was caused by a peak delay of 11 h on rainfall event 22, which is not in agreement with the sample mean values from the other treatments. The tipping buckets belonging to these two test beds were connected to a data logger different from the one that was recording data from the other test beds. One possible reason for these high peak delay results could be some technical malfunction of the data logger. However, no evidence of it could be found and so the data was kept in the analysis.

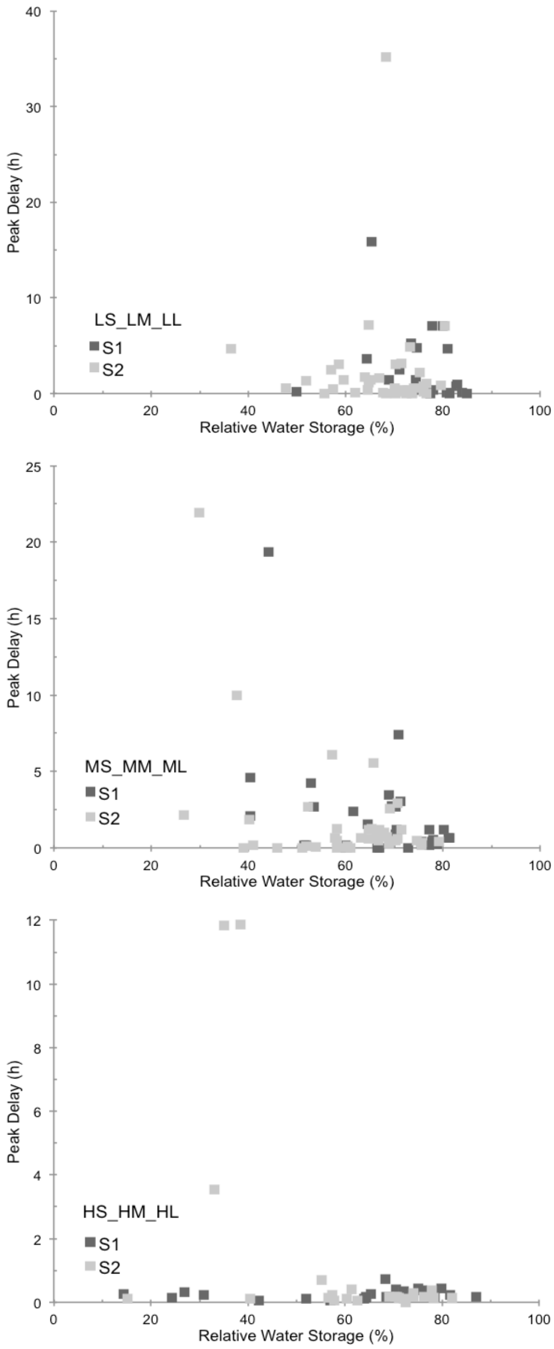


Figure 4.37 – Relation between peak delay and relative water storage in the substrate at the beginning of the rainfall by groups of maximum rainfall intensity.

Overall and not considering the rainfall class HL, S1_B showed the best performance in a larger number of classes.

In order to try to explain the variability within the rainfall classes, the peak delay results were compared to the other factor that seemed to affect the response of all the test bed treatments – the relative water content in the substrate at the beginning of the rainfall event (WS_R). Figure 4.37 contains the charts illustrating that relationship for the three groups of rainfall maximum intensity.

The first one, gathering LS, LM and LL, shows that the lower peak delay values were mostly associated with WS_R values above 65%.

For the classes with Medium maximum rainfall intensity, one of the highest peak delay values corresponded to one of the lowest WS_R and for peak delays longer than 8 hours the WS_R did not exceed 50 %. However, the lowest peak delay results did not correspond to higher relative water storage.

In the chart concerning the classes HS, HM and HL it is observable that longer peak delays were associated to relatively low WS_R values, below 40 %.

In the three situations and for WS_R values higher than 70 %, substrate 1 presented higher peak delay values than substrate 2.

Considering all the rainfall-runoff relations variables described above, S1 treatments showed a higher ability to keep its retention capacity than those with S2 treatments, even if the relative water storage in the beginning of the rainfall was high, due to a short antecedent dry period or to a previous rainfall event of large dimension.

Overall, the substrate's relative water storage at the beginning of the rainfall event seemed to have a higher impact on the retention and peak attenuation capacity than on the runoff and peak delay.

Regarding the most extreme rainfall classes (LS and HL), the differences in substrate and vegetation proprieties seemed to loose relevance. When the rainfall was of low intensity and short duration all the treatments showed good performances and when the rainfall was of high intensity and long duration, their capacity to hold water decreased, as expected, many times to a point where there were no differences between test beds. However, this does not mean the test beds' presence was irrelevant as, for example, in the retention parameter, the mean of the treatments performance, altogether, in the HL class, was 42.22 %, which still represents a meaningful impact.

In many situations the runoff response increased (higher retention, longer runoff delay, higher peak attenuation and longer peak delay) from shorter to longer rainfall classes among the classes with the same maximum rainfall intensity in 10 minutes. This led to concluding that, for the variations in the runoff behaviour between rainfall classes, the change in rainfall duration is more important than the change in its maximum intensity. This is in agreement to the results obtained in other studies, as the one of VanWoert *et al.* (2005), in which, both for a test bed covered with a mix of *Sedum* sp. plants and one without vegetation, the retention decrease from light to heavy rainfall events, ranging from 97.9 to 65% in the vegetated treatment and from 97.1 to 65.1 % in the unvegetated treatment. Mobilia *et al.* (2015) presented the range of rainfall retention results for low intensity events and for increasing duration. For events up to 10 minutes the retention was 98.5 %, up to 6 h it ranged from 91.4 to 97.9 % and for events with duration up to 3 days the retention varied from 49.8 to 80.9 %.

4.5.2.2 Effect of substrate and vegetation cover in the runoff response

The different treatments in this study resulted from the combination of two different substrate types and six different vegetation covers. In this section, the test bed treatments are compared in order to understand the impact of these variables in the rainfall-runoff relation, regardless of the rainfall classes.

The treatments with the same substrate allowed the comparison between different vegetation covers and, for the comparison of the substrates, test beds S1_R (*Rosmarinus officinalis* L.) and S2_L (*Lavandula stoechas* subsp. *luisieri*) were considered identical in terms of vegetation, because, despite being covered by different shrubs species, they have similar physiognomy and share the characteristics that influence the interception of rainfall, as leaf shape and orientation, branch angles and canopy density (Crockford and Richardson 2000).

As in this section there was no separation of rainfall events by classes, the results had a wide range of variation and their distribution was quite skewed. Therefore, both the sample mean and the sample median were used as measures of location. The mean is highly influenced by extreme values, contrary to the median, but allows comparison to other authors' results, which are many times presented that way. For the runoff delay and peak delay variables, the sample mean values should be analysed with caution. In fact, when a test bed performed complete retention, RD and PD were considered infinite, so, these variables' sample mean would only represent the events in which runoff did in fact occur. As the number of times that happened varied between test beds, their comparison would not be fair.

4.5.2.2.1 Retention

The retention capacity of the different test bed treatments is supposedly highly correlated with the physical properties of the substrates, which were described in section 4.1. Briefly, substrate 1 had a larger field capacity, which translates into a higher retention capacity, and substrate 2 had higher saturated hydraulic conductivity, in other words, a better ability to drain water. Therefore, the expectations were that S1 would present a better performance in the retention parameter of the rainfall – runoff relations.

Figures 4.38 and 4.39 compare the different treatments in terms of median and mean retention results, respectively.

S1_PM was the treatment with higher results, retaining a mean of 82 % of the rainfall water, followed by S1_R and S2_L that had similar performances (73.16 % and 72.55 % respectively). S1_B had intermediate results and S2_M and S2_BS stood out from the rest with the lowest values. The two were the only test beds with a mean retention below 70% but S2_BS had the worst performance, presenting a mean retention of 64.16 %, more than 17 % lower than S1_PM and 4 % lower than S2_M. The median provides information about what happened in 50 % of the recorded events. Although the relative position of the treatments from the best to the worst performance is the same as when analysing the mean, some new information is added. For example, S1_PM retained all the incoming rainfall in, at least, 50 % of the events, while S2_BS only retained 54.65 %.

Among the test beds with substrate 1, the decrease in mean and median retention followed the order: S1_PM > S1_R > S1_B. As for the group with S2, the trend was the expected, having the test bed with shrubs (S2_L) performed better, followed by the one with moss and, finally, by the test bed without any vegetation cover, S2_BS.

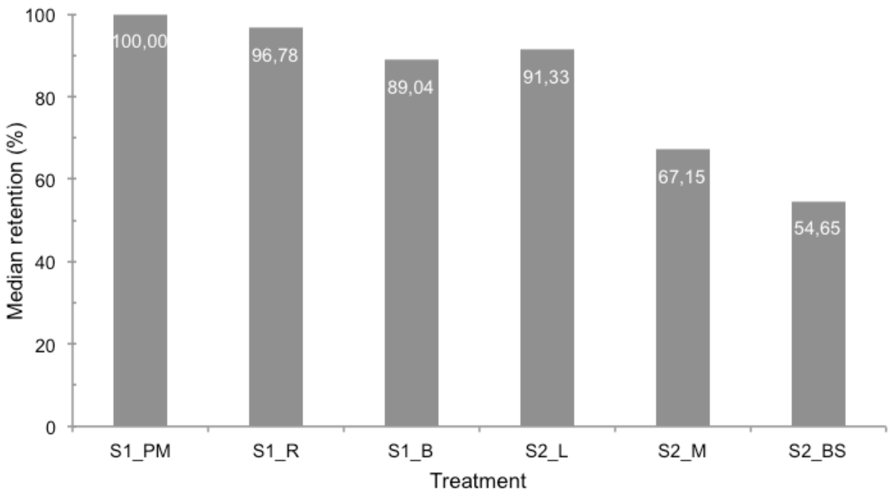


Figure 4.38 – Global median retention for each test bed treatment, considering all the recorded rainfall events.

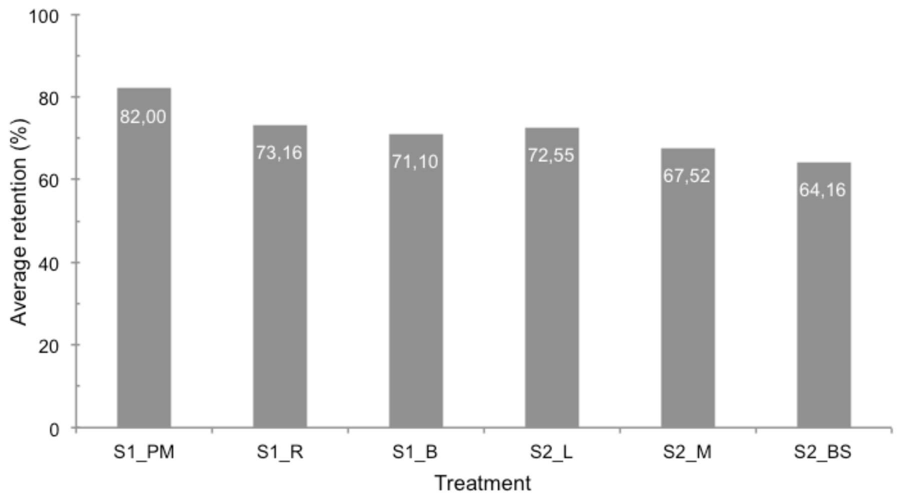


Figure 4.39 – Global mean retention for each test bed treatment, considering all the recorded rainfall events.

The test beds containing S1, together, reached a mean retention of 75.19 %, while for S2 the mean was 68.32 %. However, due to the influence of the vegetation cover, this comparison is dubious. As said before, S1_R and S2_L were used to compare the substrates. S1_R performed slightly better than S2_L (with a 0.61 % difference, on the mean comparison and 5.45 % on the median comparison), meaning that S1 could be marginally more effective retaining water than S2, matching the expected. In fact, the two test beds had close mean retention values, which led to conclude that the differences in the substrates were masked by the effect of the vegetation and that the latter had more influence in the recorded runoff.

Yilmaz *et al.* (2015) also compared green roof test plots containing vegetation to others with substrate only, having obtained 78 % retention in the substrate only test plot, 83.1 % in the test plot vegetated with *Sedum album*, 83.4 % in the test plot with *Festuca galuca* (grass) and 87.1 % retention in the test plot with *Dianthus deltoides* (mat forming forb), which had the highest values despite being installed in a shallower substrate of 80 mm, while the other test plots had 120 mm substrate. These results are comparable to the ones in our study considering that the test beds without vegetation had the lowest retention values and that the increase in plant complexity led to higher retention. Razzaghmanesh and Beecham (2014) used native vegetation and a 100 mm depth substrate in their study and obtained a mean retention of 74.02 %, very similar to the ones in the chart in Figure 4.35.

Other authors reported results concerning tests with succulent species, or succulents mixed with other native or non-native plants, having the latter generally produced higher retention results than succulents alone. For example, Voyde *et al.* (2010), reported 78 % retention from a mix of succulents and grasses in a substrate depth of 50 to 70 mm and Hutchinson *et al.* (2003), obtained 69 % retention from succulents, grasses and other herbaceous in a substrate with 120 mm of depth. Even in other cases in which only *Sedum* species were tested, they outperformed the green roof test plots without vegetation, as in Harper *et al.* (2014) and VanWoert *et al.* (2005). Fioretti *et al.* (2010) found results very similar to ours for unvegetated test beds (mean retention of 68 %) but Palla *et al.* (2010) reported only 51.5 % retention although their substrate was 200 mm deep, which is probably related to the substrate's retention capacity and to the climate conditions of the experiment site.

4.5.2.2.2 Runoff delay

The ability to delay the beginning of the runoff relatively to the beginning of the rainfall was, according to Figure 4.39, higher in test bed S1_PM, which had a median of INF (infinite), meaning that in at least 50 % of the events, there was total retention. This treatment was noticeably the most effective in the handling the runoff delay and S2_M and S2_BS were the least effective.

Regarding the group of test bed treatments with substrate 1, the median runoff delay decreased as the complexity of the vegetation cover also decreased (S1_PM > S1_R > S1_B).

As mentioned in the previous section, S1_R and S2_L were considered comparable and in this parameter the test bed with S1 performed distinctively better than the one containing S2.

Table 4.12 contains the mean runoff delay, which, as already mentioned, should be analysed with caution when being compared between treatments because it depends on the number of rainfall events that originated runoff in each test bed. That number is also in the table so it is possible to have a notion of the sample size that originated the mean value.

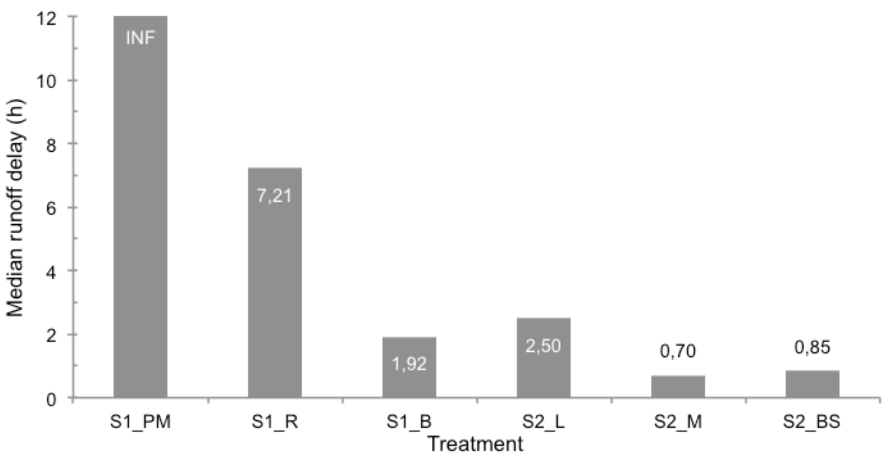


Figure 4.40 – Global median runoff delay for each test bed treatment, considering all the recorded rainfall events.

The results obtained in this study are higher than the 1.58 hours mean runoff delay results from a 30 mm depth substrate covered with *Sedum* sp. reported by Nawaz *et al.* (2015) and lower than the results of Palla *et al.* (2010) who obtained a 5.17 hours mean runoff delay from an unvegetated full scale experimental site. Their high result can perhaps be explained by the depth of the substrate layer (200 mm), 50 mm deeper than the substrate layer in our study. When Razzaghmanesh and Beecham (2014) combined four species of native plants with a substrate depth of 100 mm, they obtained a mean runoff delay of 3 h, which is in agreement with the results presented in Table 4.12. This similarity would be expected considering the use of native plants and the location of this study (Adelaide, Australia), which has a hot Mediterranean climate, with characteristics that are closer to Lisbon’s climate than the ones of other studies.

Table 4.12 – Global mean runoff delay excluding the events with 100 % retention

Test bed treatments	Events with runoff (%)	Runoff delay (h)
S1_PM	48	2.72
S1_R	61	2.39
S1_B	70	2.28
S2_L	67	1.74
S2_M	85	2.16
S2_BS	80	1.71

4.5.2.2.3 Peak attenuation

Peak attenuation was the parameter in which the mean and median results were more similar between treatments: in none of them the mean was below 88 % or the median below 94 % (Figure 4.40).

Although the differences were very slight, S1_PM had the highest mean and median. In this parameter, S2_M performed worse than S2_BS, in contrast to what had previously been verified for the retention. Given the reduced dimension of the differences between the treatments' performances, it would not be appropriate to try to draw conclusions intending to distinguish types of substrate or vegetation.

The high peak attenuation means are similar to the ones recorded in the study of Voyde *et al.* (2010) (91 % mean peak attenuation), although their tests where performed on a shallower substrate. Palla *et al.* (2010) reported 83.3% mean peak attenuation on a full scale substrate only green roof and Fioretti *et al.* (2010) obtained 89% from tests also in a green roof without vegetation.

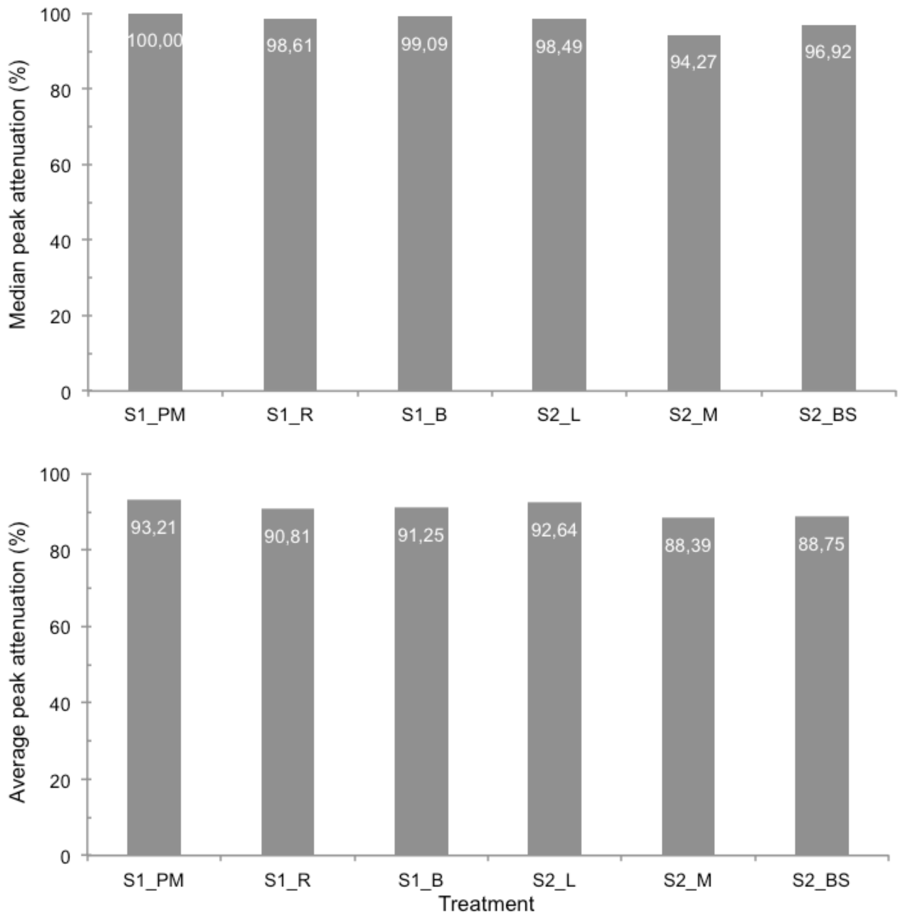


Figure 4.41 - Global median and mean peak attenuation for each test bed treatment, considering all the recorded rainfall events.

4.5.2.2.4 Peak delay

This parameter was the one with the most unexpected results, since the best and worst performances did not correspond to the same treatments as in retention, runoff delay and peak attenuation. For the same reason as for runoff delay, this parameter cannot be characterized by mean values, so the median was the measure of location used to compare between treatments.

As can be seen in Figure 4.41, S1_PM had infinite median peak delay, meaning that in at least 50 % of the events, the retention was complete. This was the treatment with the best performance in this parameter. S1_R had the next highest median peak delay, followed by S1_B, S2_L, S2_BS and S2_M, in that order. The results from S2_M and S2_BS had very close median, below 0.70 h, standing out from the rest.

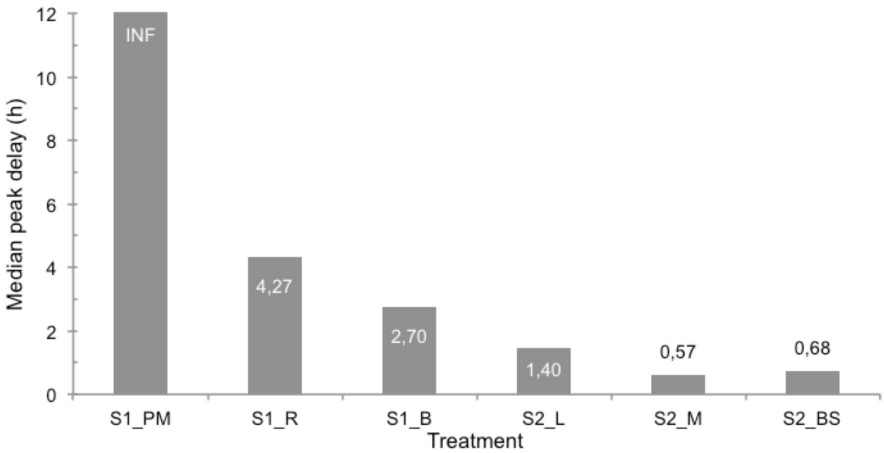


Figure 4.42 - Global median peak delay for each test bed treatment, considering all the recorded rainfall events.

Table 4.13 shows the recorded peak delay mean values obtained from the rainfall events that actually produced runoff.

Table 4.13 - Global mean peak delay excluding the events with 100 % retention

Test bed treatments	Events with runoff (%)	Peak delay (h)
S1_PM	48	0.49
S1_R	61	1.30
S1_B	70	2.55
S2_L	67	1.78
S2_M	85	2.21
S2_BS	80	0.97

Nawaz *et al.* (2015) reported a mean peak delay of 3.73 hours, which is in the same range of values as the results of this study, only slightly higher, which would not be expected considering the 30 mm depth of the substrate in Nawaz *et al.* (2015) and the use of *Sedum* species only. This study was performed under a maritime climate, with a rainfall distribution very different from a Mediterranean climate, which can perhaps explain the different behaviour, along with the characteristics of the substrate used in that study.

Overall, treatments with vegetation performed better than bare soil. It was also observable that, generally, the treatment with the best results was S1_PM, which contains different plant species and mosses. This relates to what Lundholm *et al.* (2010) concluded from their study, in which the test modules containing a combination of different species (belonging to the same or to different life-form groups) outperformed the modules containing monocultures, concerning the water capture (retention). According to the author, the best performance of the test modules containing combinations of plants can be due to the "sampling effect", where mixtures perform as well as the best monoculture because they contain the top performing species or to "transgressive overyielding", where the more biodiverse modules outperform the best monoculture, due to niche complementarity or facilitation (Lundholm *et al.* 2010; Petchey 2003)

Apart from this test bed, the general evolution of the results tended to follow the increase in complexity of the plants in this study, from the mosses to the *Rosmarinus officinalis* L. and *Lavandula stoechas* subsp. *luisieri*. This is in agreement with the soil moisture results, reported in section 4.3, which showed that the test beds containing shrubs more easily had the substrate hydraulic properties reset, during the dry periods, than the test beds containing graminoids and these more easily than the ones with moss or bare soil. The results obtained by Anderson *et al.* (2010), regarding the performance of mosses, differ from the ones here presented. In that study, mosses performed better than vascular plants, retaining almost the double. However, the moss species used were not the same as the ones used in this study and the ground coverage probably influenced the results.

5. APPLICATION OF THE RESULTS TO THE MUNICIPALITY OF LISBON

The results of the experiment described along this work provide information about the potential of green roofs to minimize the production of storm water runoff. The storm water retention and peak attenuation variables were presented as a percentage of the incoming rainfall and may be extrapolated for real scale applications.

As explored in section 2.1.2, the Municipality of Lisbon has always faced storm water management challenges. According to the reviewed literature and to the results obtained in this study, green roofs can, indeed, play a significant role as source control tool. Therefore, it was considered pertinent to develop an example of how the information obtained in this study could be applied to the reality of the city of Lisbon.

This exercise has already been performed in other cities, often by municipal initiative, and the purpose has mostly been to multiply the retention capacity of a green roof (per square meter) by the city's roof area suitable to receive green roof.

In 2005, a report on the environmental benefits and costs of green roof technology was developed for the City of Toronto, Canada (Banting *et al.* 2005). The authors established some minimum features for the green roofs: they should be extensive, have a maximum runoff coefficient of 50 % and have at least 150 mm depth where structural loads permitted. The city-scale benefits were calculated by identifying all the flat roofs (slope < 2 %) with more than 350 m^2 and assuming that at least 75 % of the roof area would be greened. The total available area obtained was of 5000 hectares, 50 million m^2, corresponding to 8 % of the city's roof area. This study had mainly an economical perspective and concluded that the total storm water benefit could range from $41.8 to $118 million.

Another study has been developed in the Assiniboine district, Winnipeg, Canada (Banting *et al.* 2005), chosen for its particular concentration of flat roof buildings and its susceptibility to drainage system overflows. Here, through aerial photograph, it was found that 20 % of the area of the district could be used for green roofs (218 773 m^2). The study results indicated that the number of overflows could be reduced in 16 % and their volume in 48 %, if all the available area for green roofs was used.

The Living Roofs and Wall Technical Report supporting London's Plan Policy of 2008 (Gedge and Newton 2008) contains a study of the possibilities of converting the city's roof space into green roofs. The estimations were made using areal photography to identify the roofs potentially suitable to receive green roofs, which were the areas that appeared to be paved or covered with shingle ballast. Then, the potential green roof space was calculated as a percentage of the total roof area of the analysed area. In this study four representative sites of the city of London were selected and the results are presented in Table5.1.

Table 5.1 - Potential green roofs area in four areas of London (Gedge and Newton 2008)

Site	Total roof area (m^2)	Potential green roof area (m^2)	%
Cannon Street	193000	61255	31
Oxford Street	143000	46330	32
Tottenham Court Road	118787	49150	41
Canary Wharf	292000	70015	24
Average per cent			32

Four larger sample areas were then selected and the benefits of green roofs were estimated based on the obtained average percentage of potential green roof area for the representative sites. Their total surface area was 10 million m^2, resulting in 3.2 million m^2 of potential green roof area. Regarding the storm water benefits, it was estimated that 80 000 m^3 (80 million L) of rainwater could be stored in those potential green roofs (Gedge and Newton 2008).

In a report concerning New York City, Rosenzweig *et al.* (2006) concluded that if green roofs were implemented on 50 % of the city's buildings that had structural capacity to receive them, they could reduce runoff in up to 10 %.

Considering all the mentioned studies, it is possible to conclude that to identify a building's capacity to receive a structure like a green roof, one should have information about the building's rooftop load capacity, which can be based on the construction techniques of the building and the roof slope.

The potential of green roofs to relieve the urban drainage systems has not yet been studied for the Municipality of Lisbon, but there are already some works that provide valuable information. Leandro (2011) developed a methodology, by using GIS software, which allowed him to identify the flat roofs of 91 % of the area of the Municipality of Lisbon (77.35 km^2 out of the 85.00 km^2 of the municipality (PORDATA 2013)). The limited study area had to do with the available satellite imaging, which did not match the municipality's limits. The author started by identifying the roofs covered by tiles through a classifying method called "supervised classification", which is based on the manual classification of a sample area and the extrapolation to the whole study area by the GIS software, applied over an image of the main active colour bands. The obtained information was then compared to the existing shapefile of the municipality's buildings. The buildings with flat roofs (without tile coverage) could be selected and their areas calculated. The author presented the results divided by parish, showing that the distribution of flat top buildings is not even across the municipality. Overall, Leandro (2011) determined the flat roof area to be 8 555 604 m^2 (12 576 buildings) (Figure 5.1). The author recognizes that his work was incomplete for application since it did not contemplate the structural conditions of the buildings, difficult to determine at a wide scale and demanding a case-by-case observation.

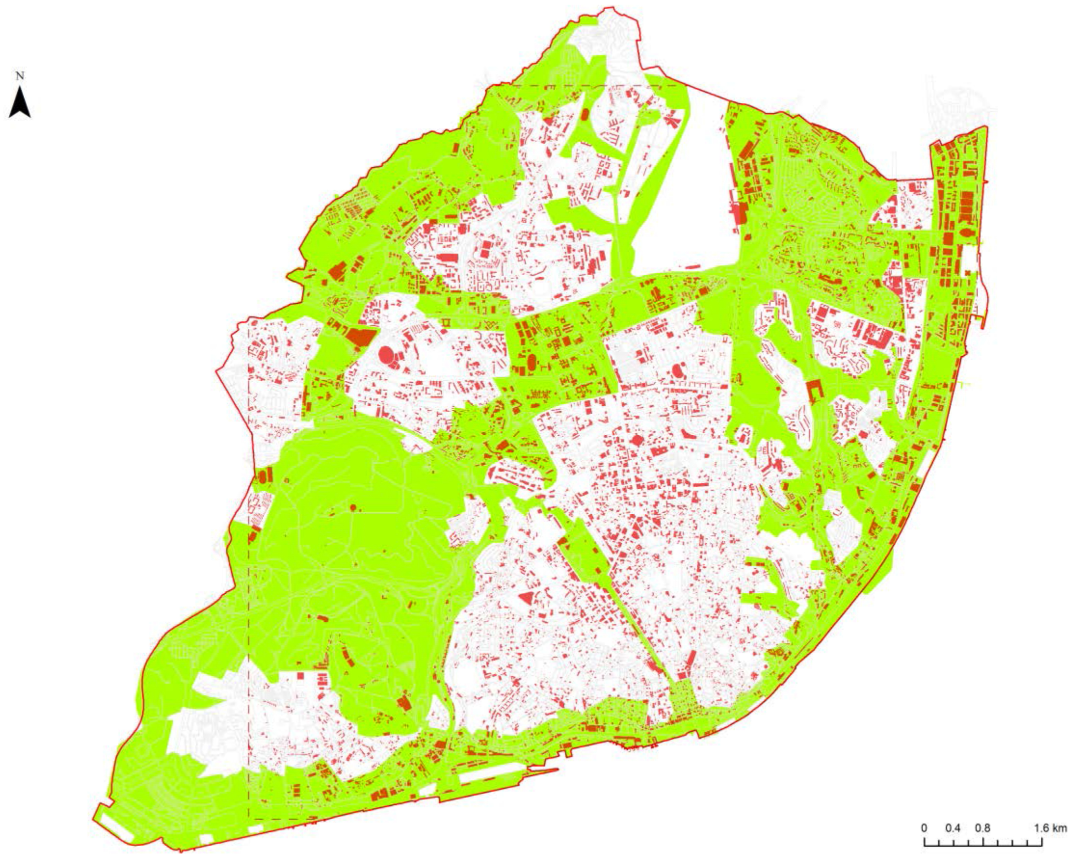


Figure 5.1 - Potential green roof buildings (red polygons), urban green infrastructure (green polygons), study area (red dashed line) and limits of the Municipality of Lisbon (red full line) (Leandro 2011).

By combining the results obtained by Leandro (2011) with the ones obtained in our study, which give us information about the rainfall retention, runoff delay, peak delay and peak attenuation capacity of a green roof, it was possible to obtain an estimate of the potential contribution of green roofs to the urban storm water management of the city of Lisbon.

The rainfall event selected to proceed with the estimation occurred between October 11th and 13th 2014, and was the largest event registered. This corresponds to a worst-case scenario as it caused, as described in section 2.1.2, major flooding in many locations of the municipality during October 13th. The test bed selected to exemplify the green roof role was the one containing the treatment S1_PM (substrate 1 and a mix of shrubs, grasses and moss), since it was the one with the best retention performance. To apply these results to the ones obtain by Leandro (2011) it was necessary to calculate the depth of rainfall water retained by square meter of test bed by multiplying the incoming rainfall depth by the calculated retention. The referred rainfall event and respective runoff event variables, obtained for the experimental site, and the retention depth are presented in Table 5.2.

Table 5.2 - Characteristics of the rainfall event of October 11-13th 2014

Rainfall event	
Depth	59.6 mm
Maximum intensity in 10 minutes	84 mm h^{-1}
Duration	46.93 h
Runoff event	
Retention	58.57 %
Runoff delay	14.37 h
Peak delay	4.08 h
Peak attenuation	77.35 %
Retained rainfall depth	34.91 mm

Considering the flat roof area estimated for the studied part of the municipality – 8 555 604 m^2 and 12 576 buildings - the maximum volume of water that could be retained would be 298 676.138 m^3 (Table 5.3). As the methodology applied by Leandro (2011) considered all the flat roof area of the study area, it was important to exclude a percentage of this value, as a green roof would never actually occupy 100 % of the roof. Thus, based on the methodologies applied in the similar studies referred above, the potential green roof area was considered to be 75 % of the flat roof area.

Table 5.3 - Potential city scale green roof retention based on the rainfall event of October 11-13th 2014

Retained rainfall depth	34.91 L m^{-2}
Flat roof area	8 555 604 m^2
75 % potential green roof area	6 416 703 m^2
Potential water storage	224 007.1 m^3

To understand the impact of the obtained values, the number of identified flat roofs was compared to the total number of buildings of the municipality (Table 5.4). The goal was to calculate the proportion of the potential green roof area relatively to the built area of the city.

Table 5.4 - Total number of buildings, number of buildings with flat roofs and impact of the potential green roof area in the Municipality of Lisbon (Leandro 2011; INE 2011)

Number of buildings in the Municipality of Lisbon	52 496
Number of buildings with flats roof in the Municipality of Lisbon	12 576
Proportion of buildings with flat roofs	23.96 %

The number of buildings potentially suitable for green roofs in the Municipality of Lisbon was estimated as 23.96 % of all the buildings in the municipality. This value is within the same range of the proportions presented in the studies developed for Winnipeg (20 %) and London (32 %) (in these cases, the potential green roof area was compared to the total area of the studied territory), while for Toronto it was lower (8%, when compared to the total roof area).

As stated previously in section 2.1.2, the new Drainage Master Plan for the Municipality of Lisbon presents, as a solution to prevent floods, the construction of underground reservoirs on the three main sewage-sheds: Alcântara, Chelas and Beirolas (Leboeuf *et al.* 2015) (Figure 5.2).

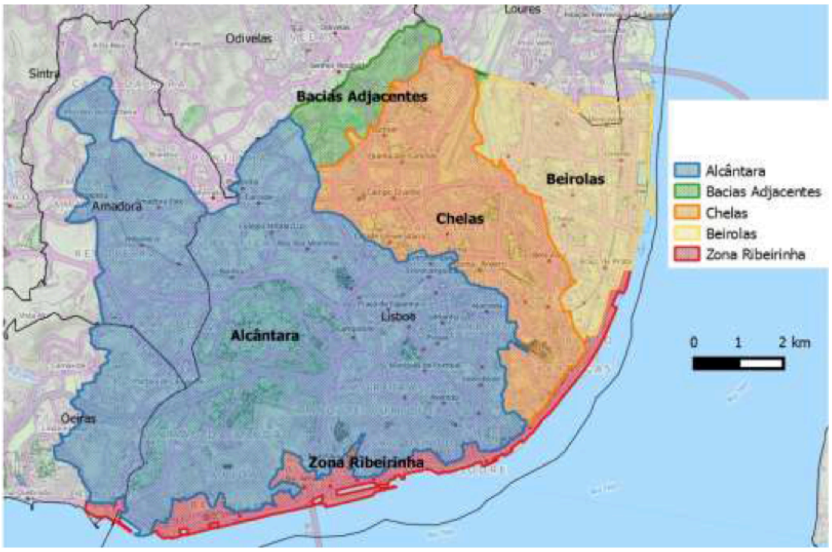


Figure 5.2 - Sewage-sheds of the Municipality of Lisbon (Leboeuf *et al.* 2015).

These reservoirs should allow a delay between the storm water storage operations and the downstream flow release, relieving the drainage systems and the treatment stations and preventing overflows. The eight proposed reservoirs totalize a volume capacity of 251100 m^3 (Leboeuf *et al.* 2015). This number is related to the amount of water that needs to be kept out of the drainage systems in order to prevent floods. Therefore, this value may be a reference to understand the impact of the potential green roof area in the storm water management of the city of Lisbon (Table 5.5).

Table 5.5 - Impact of the potential green roof area in the storm water management of the Municipality of Lisbon

Potential green roof water storage volume	224 007.1 m^3
Planned reservoirs volume capacity	251 100.0 m^3

The obtained values was quite close to the storage capacity of the reservoirs from the Drainage Master Plan, meaning that green roofs may indeed contribute to the storm water management of the municipality.

Regarding the estimated potential water retention, the results reported by Gedge and Newton (2008), for the city of London, were proportionally (80 000 m^3 for 3 200 000 m^2 of green roofs) much lower than the ones obtained in this study (224 007.1 m^3 for 6 416 703 m^2 of green roofs). The difference may be due to different rainfall patterns and different green roof characteristics. For example, if the estimates were made for a green roof with half the substrate depth, the results would be significantly reduced. However, no detailed data was found about the conditions under which that study was taken. In this study, the potential green roof water storage volume was calculated based on test beds with a substrate depth of 150 mm.

Besides all that as been mentioned, it must be considered that the load capacity of the buildings might be a limiting factor for the construction of a green roof. That kind of analysis would require further and thorough work.

As an example, the load of the green roof test beds used in this study was 59.7 kg m^{-2} when dry and 111.52 kg m^{-2} when saturated (Table 5.6).

Table 5.6 - Green roof test beds layers' dry and saturated weight

Layer	Dry weight	Saturated weight
Substrate 1 (150 mm)	57.45 kg m^{-2}	101.25 kg m^{-2}
ZinCo SSM 45 non woven blanket	0.47 kg m^{-2}	5.47 kg m^{-2}
ZinCo Floradrain FD 25E drainage layer	1.70 kg m^{-2}	4.7 kg m^{-2}
ZinCo SF non woven blanket	0.10 kg m^{-2}	0.1 kg m^{-2}
Total	59.72 kg m^{-2}	111.52 kg m^{-2}

Some buildings may not be able to support the weight of such a 150 mm substrate depth green roof, what does not mean that the construction of a green roof would be impossible, but it would require a shallower substrate layer. Although the thinner the substrate, the smaller its retention capacity would be (VanWoert *et al.* 2005; Palla *et al.* 2010; Fassman-Beck *et al.* 2013; Razzaghmanesh and Beecham 2014; Lee *et al.* 2015; Yilmaz *et al.* 2015) there still would be a significant reduction and delay of the runoff amount, as was proven in some of the studies referred in section 2.5 and in Appendix 2.

Generally, in the city of Lisbon, the buildings constructed after 1950 are made of concrete (LNEC 2015), what makes them more probably suitable for roof greening. The load capacity requirements are more demanding for intensive green roofs. Considering the extensive type, these might also be applied over resistant wood or metal sheet rooftops (Lopes 2004 cited by Raposo 2013). The regulatory overload for accessible rooftops, according to the rules and regulations in force is 200 kg m^{-2}, and for inaccessible rooftops is 100 kg m^{-2} (Raposo 2013). This puts the green roof test beds evaluated in this study in the first category, which means they would suit all building's roofs identified as accessible.

It is also probable that the analysis made by Leandro (2011), due to its automatized nature, led to the selection of polygons with very small areas that would not be viable for the implementation of a green roof. By excluding those polygons, the potential green roof area would decrease, as well as the associated water retention potential. Filtering the available information by taking this into account could lead to more accurate results.

Overall and although the estimates presented in this section, for the Municipality of Lisbon, can be an upper bound, green roofs seem to have the potential to play a considerable positive role as a storm water management tool in the urban space, under Mediterranean climate and using native plants.

CONCLUSIONS

The difficulties related to storm water management are a consequence of urban development, urban population growth and increase of impervious surface areas. Green roofs may work as a source control measure as they have the ability to retain rainfall. The main goal of this study was to quantify the capacity of a green roof to the relief of urban drainage systems, by analyzing its hydrological performance, using native species in a Mediterranean climate.

The months through which this study was developed correspond to most of the wet season of 2014/2015. This hydrological year may be considered average, as the total rainfall was not very different from the 30 years average. However, some months were unusually wet, especially November.

The 6 implemented experimental treatments differed in substrate and vegetation cover. Their response to the incoming rainfall resulted from the substrate and vegetation properties and translated into different runoff behaviors, which were measured through the variables: retention, runoff delay, peak attenuation and peak delay.

Globally, the runoff response was in agreement with the range of values reported by other authors. The retention ranged from 5.24 to 100 %, with a mean of 71.43 % and a median of 83.90 %. The runoff delay ranged from 0 to 35.17 h, its mean and its median were 1.96 h and 0.40 h, respectively. The peak attenuation showed high percentages across most of the events, ranging from 29.55 to 100 %, with a mean of 90.59 % and a median of 98.46 %. The peak delay had a mean of 1.6 h and a median of 0.40 h, ranging from 0 to 35.17 h.

When the behaviour of the treatments was analysed in a rainfall class basis, it was found that, regarding the retention, the higher results corresponded to the rainfall class of low maximum intensity and short duration (LS) and the lower results to the high maximum intensity and medium (HM) or long (HL) duration. The largest rainfall event for which the treatments retained 100 % had 21.66 mm h^{-1} maximum intensity over 10 minutes and lasted for 0.27 hours (HS). When the rainfall events were analysed altogether and the treatments were compared, S1_PM showed higher retention results, retaining a mean of 82 % of the rainfall water, followed by S1_R and S2_L (73.16 % and 72.55 % respectively). S1_B had intermediate results and S2_M and S2_BS stood out from the rest with the lowest values. The comparison of the substrates was made through the test beds with shrubs, S1_R and S2_L. The treatments had close results, but S1_R performed slightly better, suggesting that S1 was better at retaining water, as it was expected considering the substrate properties. However, the close results led to suspect that the differences in the substrates were masked by the effect of the vegetation and that the latter had more influence in the recorded runoff, as it was put in evidence by the differences in the performance of the vegetated and the unvegetated test beds.

Contrary to what had happened with the retention parameter, many times, higher runoff delay sample means were associated with the long or medium duration rainfall classes, probably due to the combination of more than one rainfall event. When comparing the test bed treatments for the runoff delay by their median results S1_PM showed best performance, presenting a median of INF (infinite), which means that, in at least 50 % of the events, this test beds did not produce runoff. S2_M and S2_BS had the worst performances. Regarding this variable, the treatment containing shrubs and substrate 1 performed distinctively better than the one containing shrubs and substrate 2.

The peak delay, which was analysed in a similar way as the runoff delay, was the least predictable variable, not varying according to what was expected. S1_PM, which had the best performance in the other variables, did not achieve more than 2 hours of peak delay in any of the studied rainfall classes. Despite this analysis, in which only the events that produced runoff in all the test beds were compared, S1_PM had infinite median peak delay, S1_R (4.27 h) had the next highest median peak delay, followed by S1_B (2.70 h), S2_L (1.40 h), S2_BS and S2_M, in that order. The results from S2_M and S2_BS were 0.57 and 0.68 h, respectively.

Peak attenuation had much less variability of results than the retention parameter, since the attenuation of the rainfall peak was very close to 100 % for several events. Peak attenuation was lower for treatments with less complex vegetation. This was the parameter in which the mean and median results were more similar between treatments: in none of them the mean was below 88 % or the median below 94 %.

Considering all the variables and in general, the performance of the treatments was better as the vegetation cover complexity increased. For all the studied variables, when the rainfall event was of low intensity and short duration all the treatments showed good performances. When the rainfall event was of high intensity and long duration, they all showed worse performances and the differences between treatments were barely observable. However, when situations like that occurred, the effect of the presence of the green roof test beds was still very important as, in the HL class, the mean retention of the treatments, altogether, was 42.22 %.

The factors influencing the hydrological behaviour of the green roof test beds were many, making it difficult to predict their response. There was, a certain homogeneity in the response considering the constant factors - substrate and vegetation properties. However, even when the rainfall events were grouped in classes, small variations in maximum intensity, duration or total depth produced different responses, leading to a high variability of results. Despite the characteristics of each rainfall event, the conditions of the test beds by the time it started conditioned the runoff response. Through the measurement of the relative water storage in the substrate at the beginning of the rainfall events, it was possible to understand that when the substrate had more water at the beginning of the rainfall, its performance was poorer than when the water storage was low. Overall, the substrate's relative water storage at the beginning of the rainfall event seemed to condition the retention and peak attenuation response more than the runoff and peak delay's.

Among the four rainfall-runoff relation variables studied, the retention was the one in which the behaviour of the test beds was more in agreement to what was expected, considering the substrates and the vegetation characteristics. This suggests that for the other variables, the characteristics of the rainfall events and the water storage at the beginning of the events were more significant for the treatments response than the treatments configuration in itself.

Overall, treatments with vegetation performed better than bare soil and shrubs performed better than grasses most of the times. It was also observable that, in general, the treatment with the best results was S1_PM, which contained different plant species and moss, combining complementary functions and structures and maximizing the services expected from a green roof.

When the retention values obtained in the experimental study were extrapolated to the Municipality of Lisbon, the results exceeded the expectations. It was estimated that, if implemented, green roofs would have the potential to retain over 224 000 m^3 of rainfall water (58.6 %). The estimations were made considering a large rainfall event that caused floods in many locations of the municipality, meaning that the retention capacity would be even higher (in percentage) for more frequent rainfall episodes. The obtained values are comparable to the volume capacity of the reservoirs proposed in the Urban Drainage Master Plan, leading to conclude that the implementation of green roofs in the buildings of the municipality could, in fact, have a significant impact in the storm water management.

Besides, green roofs have proven to bring many other benefits to the urban space as a complement to the urban green infrastructure, increasing the connections between bigger green areas, working as "stepping stones" of biodiversity and vegetation. However, by analysing the available literature, it was possible to understand that, as a water management tool at a watershed scale, green roofs may be more effective when combined with other environmentally friendly source control strategies, for example infiltration basins and permeable pavements.

The creation of policies regulating the implementation of green roofs, for example, by rewarding the developers who included them in their urbanization projects by reducing taxes and fees, would benefit the municipality.

It is also important to keep in mind that the presented estimates correspond to the characteristics of the green roof test beds used in the experimental study. Variations in vegetation species and configuration, substrate type, depth and slope, location and climate will highly influence the runoff response.

The use of native plants did not present a disadvantage in the performance of the test beds when compared to other studies that used *Sedum* species. This means that by using native species, one will not be sacrificing the benefits of the green roof and will be promoting the increase of biodiversity and guaranteeing a low maintenance system.

The Mediterranean climate presents challenges due to the distribution of the rainfall through the seasons. However, the study here developed has proven that it is possible to achieve performances similar to the ones reported by other authors in temperate or maritime climates.

For further research it might be interesting to try other native species, choosing them by their adaptation to habitats with similar conditions to the ones that are found on a green roof. To better explain the differences between the treatments it might also be interesting to study the plant coverage and growth, which can have an impact in the test bed properties and runoff response, despite of the vegetation type.

REFERENCES

Anderson, Malcolm, John Lambrinos, and Erin Schroll. 2010. “The Potential Value of Mosses for Stormwater Management in Urban Environments.” *Urban Ecosystems* 13 (3): 319–32.

Assembleia Municipal de Lisboa. 2015. *Cheias em Lisboa: causas das sistemáticas inundações que assolaram Lisboa, nos meses de Setembro e Outubro de 2014*. 4ª Comissão Permanente - Ambiente e Qualidade de Vida. Lisbon.

Banting, Doug, Hitesh Doshi, James Li, Paul Missios, Angela Au, Beth Anne Currie, and Michael Verrati. 2005. *Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto*. Ryerson University: Department of Architectural Science.

Barker, George. 1997. “A Framework for the Future: Green Networks with Multiple Uses in and around Towns and Cities.” 256. *English Nature Research Reports*. English Nature.

Bates, Bryson, Zbigniew W. Kundzewicz, Shaohong Wu, and Jean Palutikof. 2008. *Climate Change and Water: Technical Paper.* Intergovernmental Panel on Climate Change. IPCC Secretariat. Geneva.

Beecham, Simon C., Mostafa Razzaghmanesh, and Fatemeh Kazemi. 2012. *Introducing Green Infrastructure into the Built Environment of Adelaide*. University of South Australia: School of Natural and Built Environments, Australia.

Berghage, Robert D., David Beattie, Albert R. Jarrett, Christine Thuring, Farzaneh Razaei, and Thomas P. O’Connor. 2009. *Green Roofs for Stormwater Runoff Control*. Office of Research and Development, National Risk Management Research Laboratory - Water Supply and Water Resources Division, United States Environmental Protection Agency (USEPA). USA.

Berndtsson, Justyna Czemiel. 2010. “Green Roof Performance towards Management of Runoff Water Quantity and Quality: A Review.” *Ecological Engineering* 36 (4): 351–60.

Berretta, Christian, Simon Poë, and Virginia Stovin. 2014. “Moisture Content Behaviour in Extensive Green Roofs during Dry Periods: The Influence of Vegetation and Substrate Characteristics.” *Journal of Hydrology* 511: 374–86.

Brandão, Cláudia, Rui Rodrigues, and J. Costa. 2001. *Análise de Fenómenos Extremos - Precipitações Intensas em Portugal Continental.* Direcção dos Serviços de Recursos Hídricos. Lisbon.

Brenneisen, Stephan. 2002. “Green Roofs - How Nature Returns to the City.” In *International Conference on Urban Horticulture* 643, 289–93.

Brenneisen, Stephan. 2006. “Space for Urban Wildlife: Designing Green Roofs as Habitats in Switzerland.” *Urban Habitats* 4 (1): 27–36.

Campbell Scientific. 2006. *CS616 and CS625 Water Content Reflectometers Instruction Manual*. Campbell Scientific. Logan, Utah, USA.

Carapeto, A., C. T. Gomes, U. Schwarzer, A. Silva, V. Silva, F. Clamote, C. Aguiar, and N. Guiomar. 2015. Lavandula Stoechas L. Subsp. Luisieri - Mapa de Distribuição. Flora-On: Flora de Portugal Interactiva, Sociedade Portuguesa de Botânica. Accessed [September 22]. Available from http://www.flora-on.pt/#wLavandula+stoechas+subsp.+luisieri.

City of Toronto website. 2015. *Green Roofs - Environment - City Planning* | *City of Toronto*. Accessed [June 4]. Available from http://www1.toronto.ca/wps/portal/contentonly?vgnextoid=3a7a036318061410VgnVCM10000071d60f89RCRD.

City-data. 2015. *Michigan - Climate*. Accessed [August 24]. Available from http://www.city-data.com/states/Michigan-Climate.html.

City-data. 2015a. *Missouri - Climate*. Accessed August 24. http://www.city-data.com/states/Missouri-Climate.html.

City-data. 2015b. *North Carolina - Climate*. Accessed [August 24]. Available from http://www.city-data.com/states/North-Carolina-Climate.html.

City-data. 2015c. Pennsylvania - Climate. August 24. http://www.city-data.com/states/Pennsylvania-Climate.html.

Climate-Data. 2015. *Climate: Seoul*. Accessed [August 24]. Available from http://en.climate-data.org/location/718563/.

CML, Câmara Municipal de Lisboa. 2010. *Relatório Síntese de Caracterização Biofísica de Lisboa - Revisão do Plano Director Municipal de Lisboa*. Lisbon.

CML, Câmara Municipal de Lisboa. 2012. "Planta de Ordenamento - Riscos Naturais e Antrópicos." *Plano Director Municipal*. Lisbon.

CML, Câmara Municipal de Lisboa. 2015c. *Plano Geral de Drenagem de Lisboa*. Accessed [July 17]. Available from https://vimeo.com/132020170

CML. 2015a. *Incentivos Fiscais à Reabilitação Urbana.* Available from http://www.cm-lisboa.pt/viver/urbanismo/reabilitacao-urbana/incentivos-fiscais-e-operacionalizacao/incentivos-fiscais.

CML. Câmara Municipal de Lisboa. 2015b. *Reduções e Isenções de Taxas para a Reabilitação Urbana*. Available from http://www.cm-lisboa.pt/viver/urbanismo/reabilitacao-urbana/incentivos-fiscais-e-operacionalizacao/reducoes-e-isencoes-de-taxas.

Crockford, R. H., and D. P. Richardson. 2000. "Partitioning of Rainfall into Throughfall, Stemflow and Interception: Effect of Forest Type, Ground Cover and Climate." *Hydrological Processes* 14 (16-17): 2903–20.

Davis, George W., and David M. Richardson. 1995. "Mediterranean-Type Ecosystems: The Function of Biodiversity". Vol. 109. *Ecological Studies*. Springer-Verlag.

Decreto Regulamentar nº 11/2009 de 29 de Maio. *Diário da República, 1.a série—Nº 104—29 de Maio de 2009.* Direcção-Geral do Ordenamento do Território e Desenvolvimento Urbano. Lisbon

Dunnett, Nigel, Ayako Nagase, Rosemary Booth, and Philip Grime. 2008. "Influence of Vegetation Composition on Runoff in Two Simulated Green Roof Experiments." *Urban Ecosystems* 11 (4): 385–98.

Dvorak, Bruce, and Astrid Volder. 2010. "Green Roof Vegetation for North American Ecoregions: A Literature Review." *Landscape and Urban Planning* 96 (4): 197–213.

Earth Pledge Foundation. 2005. *Green Roofs: Ecological Design and Construction*. Schiffer Pub Limited.

EEA, European Environment Agency. 2009. *Key Environmental Issues Facing Europe*. Copenhagen: European Environment Agency.

Expresso. 2015. *Câmara de Lisboa Arranca Com Plano de Drenagem Na Próxima Semana*. Jornal Expresso. October 14th 2014. Accessed [May 29]. Available from http://expresso.sapo.pt/sociedade/camara-de-lisboa-arranca-com-plano-de-drenagem-na-proxima-semana=f893634.

Fassman-Beck, Elizabeth, Emily Voyde, Robyn Simcock, and Yit Sing Hong. 2013. "4 Living Roofs in 3 Locations: does configuration affect runoff mitigation?" *Journal of Hydrology* 490: 11–20.

Fioretti, R., A. Palla, L. G. Lanza, and P. Principi. 2010. “Green Roof Energy and Water Related Performance in the Mediterranean Climate.” *Building and Environment* 45 (8): 1890–1904.

FLL, Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau. 2002. *Guidelines for the Planning, Execution and Upkeep of Green-Roof Sites.* Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau. Bonn, Germany.

Flora-on. 2015a. Brachypodium phoenicoides. Accessed [September 22]. Available from http://www.flora-on.pt/#/1brachypodium+phoenicoides.

Flora-on. 2015b. Lavandula stoechas subsp. luisieri. Accessed [September 22]. Available from http://www.flora-on.pt/#/1lavandula+luisieri.

Flora-on. 2015c. Rosmarinus officinalis. Accessed [September 22]. Available from http://www.flora-on.pt/#/1rosmarinus+officinalis.

Gedge, Dusty, and John Newton. 2008. *Living Roofs and Walls Technical Report: Supporting London Plan Policy*. Design for London - Greater London Authority. Available from https://www.london.gov.uk/sites/default/files/archives/uploads-living-roofs.pdf.

Getter, Kristin L., and D. Bradley Rowe. 2006. “The Role of Extensive Green Roofs in Sustainable Development.” *HortScience* 41 (5): 1276–85.

Getter, Kristin L., D. Bradley Rowe, and Jeffrey A. Andresen. 2007. “Quantifying the Effect of Slope on Extensive Green Roof Stormwater Retention*.” Ecological Engineering* 31 (4): 225–31.

Grant, Gary, *et al.*. 2006. *Green Roofs and Façades*. UK: IHS BRE Press Bracknell.

Grant, Gary, Luke Engleback, Barry Nicholson, D. Gedge, M. Frith, and P. Harvey. 2003. “Green Roofs: Their Existing Status and Potential for Conserving Biodiversity in Urban Areas." *English Nature Research Reports* 498: 9–59.

GRO, Green Roof Organisation. 2014. *The GRO Green Roof Code - Green Roof Code of Best Practice for the UK 2014*. Groundwork Sheffield.

Harper, Grace E., Matt A. Limmer, W. Eric Showalter, and Joel G. Burken. 2015. “Nine-Month Evaluation of Runoff Quality and Quantity from an Experiential Green Roof in Missouri, USA.” *Ecological Engineering* 78: 127–33.

Hathaway, Amy Moran, William F. Hunt, and Gregory D. Jennings. 2008. “A Field Study of Green Roof Hydrologic and Water Quality Performance.” *Transactions of the American Society of Agricultural and Biological Engineers* (ASABE) 51 (1): 37–44.

Hendershot, W.H., Lalande, H., Duquette, M.. "Spil Reaction and Exchangeable Acidity". In: Carter, M.R., and E.G. Gregorich. 2008. *Soil Sampling and Methods of Analysis*. 2nd ed. Canadian Society of Soil Science. CRC Press. Chapter 16. pp 173-177

Herman, Robert. 2003. “Green Roofs in Germany: Yesterday, Today and Tomorrow.” *Greening Rooftops for Sustainable Communities*. Chicago. pp 41–45.

Hobbs, R.J., D. M. Richardson, and G. W. Davis. 1995. “Mediterranean-Type Ecosystems: Opportunities and Constraints for Studying the Function of Biodiversity.” In *Mediterranean-Type Ecosystems: The Function of Biodiversity*. Springer-Verlag.

Hutchinson, Doug, Peter Abrams, Ryan Retzlaff, and Tom Liptan. 2003. *Stormwater Monitoring Two Ecoroofs in Portland, Oregon, USA*. City of Portland: Bureau of Environmental Services.

INE, Instituto Nacional de Estatística. 2011. *Censos 2011*. "Censos 2011 - Importação Dos Principais Dados Alfanuméricos e Geográficos (BGRI)". Accessed [October 2]. Available from http://mapas.ine.pt/download/index2011.phtml.

IPMA, Instituto Português do Mar e da Atmosfera. 2015a. *Normais Climatológicas*. Accessed [August 24]. Available from https://www.ipma.pt/pt/oclima/normais.clima/.

IPMA. 2015b. *Normais Climatológicas - Precipitação*. Accessed [August 24]. Available from https://www.ipma.pt/pt/oclima/normais.clima/1981-2010/012/.

IPMA. 2015c. *Normais Climatológicas - Temperatura*. Accessed [August 2]. Available from https://www.ipma.pt/pt/oclima/normais.clima/1981-2010/012/.

Johnston, Jacklyn, and John Newton. 2004. *Building Green: A Guide to Using Plants on Roofs, Walls and Pavements*. Greater London Authority: Ecology Unit. Lavandula%252bluisieri%2526s%253ddesc%252528plant_merged%252529%2526sl%253dplantForm%26query%3drosmarinus%2bofficinalis%26aliaspath%3d%252fplants%252fsearch-results.

Lawlor, Gail, Beth Anne Currie, Hitesh Doshi, and Ireen Wieditz. 2006. *Green Roofs: A Resource Manual for Municipal Policy Makers*. Canada: Canada Mortgage and Housing Corporation.

Leandro, Alexandre Miguel. 2011. *Avaliação da Capacidade de Instalação de Telhados Verdes na Cidade de Lisboa com Recurso a SIG e Detecção Remota*. Master Degree Thesis in Pysical Geography and Territorial Planning. Instituto de Geografia e Ordenamento do Território. University of Lisbon. Lisbon.

Leboeuf, Yohann, Zélia Fernandes, João Guimarães, Joana Simões, Patrícia Ribeiro, Filipa Ferreira, Rodrigo Proença de Oliveira, António Monteiro, and José Saldanha Matos. 2015. *Plano Geral de Drenagem de Lisboa 2016-2030*. Lisbon: Câmara Municipal de Lisboa.

Lee, Ju Young, Min Jung Lee, and Mooyoung Han. 2015. “A Pilot Study to Evaluate Runoff Quantity from Green Roofs.” *Journal of Environmental Management* 152: 171–76.

Linz, Planungsamt. 2002. *Grünflächenplan Der Stadt Linz 2001*.

Liptan, T. 2005. “Portland: A New Kind of Stormwater Management.” *Earthpledge, Green Roofs: Ecological Design and Construction*. Atglen: Schiffer Bookspp.

Liu, Karen, and John Minor. 2005. *Performance Evaluation of an Extensive Green Roof*. Presentation at Green Rooftops for Sustainable Communities. Washington DC. 1–11.

LNEC, Laboratório Nacional de Engenharia Civil. 2015.. *Edifícios com Estrutura Mista de Betão e Alvenaria (1940 a 1960*). Departamento de Estruturas, Núcleio de Engenharia Sísmica e Dinâmica de Estruturas. 2005. Accessed [September 25]. Available from http://www-ext.lnec.pt/LNEC/DE/NESDE/divulgacao/Edif_1940_1960.html.

Lopes, J. 2004. *As Especificidades Das Coberturas Ajardinadas*. Laboratório Nacional de Engenharia Civil. Lisbon.

LQARS, Laboratório Químico Agrícola Rebelo da Silva. 2006. *Manual de Fertilização Das Culturas*. Lisbon: INIAP.

Lundholm, Jeremy, J. Scott MacIvor, Zachary MacDougall, and Melissa Ranalli. 2010. “Plant Species and Functional Group Combinations Affect Green Roof Ecosystem Functions.” *Plos One* 5 (3): e9677.

MacIvor, J. Scott, and Jeremy Lundholm. 2011. “Performance Evaluation of Native Plants Suited to Extensive Green Roof Conditions in a Maritime Climate.” *Ecological Engineering* 37 (3): 407–17.

Magalhães, Manuela Raposo. 2001*. A Arquitectura Paisagista - Morfologia e Complexidade*. 1st ed. Lisbon: Editorial Estampa.

Marques, José Moreira. 2008. Árvores e Arbustos de Portugal. Lisboa: Argumentum.

Mishra, A. 2004. “Canadian Public Policy and Green Roofs: Moving from Policy to Practice.” In Proc. of *2nd North American Green Roof Conference: Greening Rooftops for Sustainable Communities*. Portland, Oregon, USA. 2–4.

Mobilia, Mirka, Antonia Longobardi, and Joachim Friedrich Sartor. 2015. “Impact of Green Roofs on Stormwater Runoff Coefficients in a Mediterranean Urban Environment.” *Recent Advances in Urban Planning, Sustainable Development and Green Energy*.

Nagase, Ayako, and Nigel Dunnett. 2012. “Amount of Water Runoff from Different Vegetation Types on Extensive Green Roofs: Effects of Plant Species, Diversity and Plant Structure.” *Landscape and Urban Planning* 104 (3): 356–63.

Nawaz, Rizwan, Angus McDonald, and Sophia Postoyko. 2015. “Hydrological Performance of a Full-Scale Extensive Green Roof Located in a Temperate Climate.” *Ecological Engineering* 82: 66–80.

Ngan, Goya. 2004. *Green Roof Policies: Tools for Encouraging Sustainable Design*. Canada: Landscape Architecture Canada Foundation.

Oberndorfer, Erica, Jeremy Lundholm, Brad Bass, Reid R. Coffman, Hitesh Doshi, Nigel Dunnet, Stuart Gaffin, Manfred Kõler, Karen Ky Liu, and Bradley Rowe. 2007. “Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services.” *BioScience* 57 (10): 823–33.

Oliveira, Pedro Elias. 2005. *Inundações na Cidade de Lisboa: implicações da melhoria do sistema de drenagem artificial após os anos 60*. University of Lisbon: Center of Geographic Studies.

Önder, Serpil. 2014. “Advances of Green Roofs for Environment in Urban Areas.” *Turkish Journal of Agricultural and Natural Sciences*. Special issue 2.

Palla, Anna, Ilaria Gnecco, and Luca G. Lanza. 2010. “Hydrologic Restoration in the Urban Environment Using Green Roofs.” *Water* 2 (2): 140–54.

Peck, Steven W. 2002. *Green Roofs: Infrastructure for the 21st Century*. Clean Air Partnership 1st Annual Urban Heat Island Summit. Toronto.

Petchey, Owen L. 2003. “Integrating Methods That Investigate How Complementarity Influences Ecosystem Functioning.” *Oikos* 101 (2): 323–30.

Pevzner, Amy. 2014. *Living Architecture: Green Roofs For Public Buildings - A strategy for smarter roofing decisions.* General Services Administration: Energy & Sustainability/Safety & Environmental Branch. Facilities Management & Services Programs Division PBS, Region 9.

Platt, Rutherford H. 2004. “Regreening the Metropolis: Pathways to More Ecological Cities: Keynote Address.” *Annals of the New York Academy of Sciences* 1023 (1): 49–61.

Pordata. 2013. Retrato de Lisboa PORDATA 2011. 1st ed. Lisbon: Fundação Francisco Manuel dos Santos.

Porto, M., A. Carapeto, F. Clamote, P. V. Araújo, A. J. Pereira, J. D. Almeida, and E. Marabuto. 2015. Rosmarinus officinalis L. - Mapa de Distribuição. Flora-On: Flora de Portugal Interactiva, Sociedade Portuguesa de Botânica. Accessed [September 22]. Available from http://www.flora-on.pt/#wRosmarinus+officinalis.

Porto, M., E. Portela-Pereira, R. Caraça, A. Carapeto, A. J. Pereira, S. Ribeiro, J. D. Almeida, and P. Pereira. 2015. Brachypodium phoenicoides (L.) Roem. & Schult. - Mapa de Distribuição. Flora-On: Flora de Portugal Interactiva, Sociedade Portuguesa de Botânica. Accessed [September 22]. Available from http://www.flora-on.pt/#wBrachypodium+phoenicoides.

Público. 2015. "Chuva Intensa Corta Estradas E Provoca Inundações Em Lisboa". *Jornal Público*. October 13th 2014. Accessed [July 28]. Available from http://www.publico.pt/local/noticia/chuva-intensa-em-lisboa-obriga-ao-corte-da-calcada-de-carriche-1672752.

Raposo, Fausto Miguel Ferreira. 2013. *Manual de Boas Práticas de Coberturas Verdes*. Master Degree Thesis in Construction and Rehabilitation, University of Lisbon: Instituto Superior Técnico.

Razzaghmanesh, M., and S. Beecham. 2014. "The Hydrological Behaviour of Extensive and Intensive Green Roofs in a Dry Climate." *Science of the Total Environment* 499 (November): 284–96.

Regime Jurídico Da Reabilitação Urbana. 2009. Decreto-Lei n.º 307/2009 de 23 de Outubro. *Diário da República, 1ª série—Nº 206—23 de Outubro de 2009*. Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional. Lisbon.

Reinhardt, A., and B. Schaffner. 1999. *Evaluation von Energiesparaktionen Des Kantons Basel-Stadt*. Unpublished term thesis ETH Zürich, Department of Environmental Sciences.

RHS, Royal Horticultural Society. 2015. Rosmarinus officinalis. Accessed [September 22]. Available from https://www.rhs.org.uk/Plants/16099/Rosmarinus-officinalis/Details?returnurl=%2fplants%2fsearch-results%3fform-mode%3dtrue%26context%3db%253d0%2526hf%253d10%2526l%253den%2526q%253d

Richards, L. A., and Milton Fireman. 1943. "Pressure-Plate Apparatus for Measuring Moisture Sorption and Transmission by Soils." *Soil Science* 56 (6): 395–404.

Roy, Allison H., Seth J. Wenger, Tim D. Fletcher, Christopher J. Walsh, Anthony R. Ladson, William D. Shuster, Hale W. Thurston, and Rebekah R. Brown. 2008. "Impediments and Solutions to Sustainable, Watershed-Scale Urban Stormwater Management: Lessons from Australia and the United States." *Environmental Management* 42 (2): 344–59.

Rutherford, P.M., McGill, W.B., Arocena, J.M., Figueiredo, C.T., "Total Nitrogen". In: Carter, M.R., and E.G. Gregorich. 2008. *Soil Sampling and Methods of Analysis*. 2nd ed. Canadian Society of Soil Science. CRC Press. Chapter 22. pp 239-250.

Saldanha Matos, José de, Rodrigo Proença de Oliveira, António Monteiro, and Manuel Lacerda. 2006. "O Plano Geral de Drenagem de Águas Residuais Da Cidade de Lisboa." *Águas e Resíduos, III*, nº. 2 (December).

Soares, Ana, Bruno Pereira, Carmen Santos, Catarina Ramos, Pedro Oliveira, and Teresa Vaz. 2005. "*Inundações Urbanas: O Caso das Ruas de Sta Marta, S. José e Portas de Stº Antão* (Lisboa)". University of Lisbon:Department of Geography and Center of Geographic Studies.

Stakman, W. P. 1974. "Measuring Soil Moisture." *Drainage Principles and Applications*, 221–51.

Stolte, J. 1997. "Determination of the Saturated Hydraulic Conductivity Using the Constant Head Method." *Manual for Soil Physical Measurements*. Tech. Doc 37: 27–32.

Stovin, Virginia, Gianni Vesuviano, and Hartini Kasmin. 2011. "The Hydrological Performance of a Green Roof Test Bed under UK Climatic Conditions." *Journal of Hydrology* 414: 148–61.

Stovin, Virginia. 2010. "The Potential of Green Roofs to Manage Urban Stormwater." *Water and Environment Journal* 24 (3): 192–99.

Thompson, J. William, and Kim Sorvig. 2007. *Sustainable Landscape Construction: A Guide to Green Building Outdoors*. Washington: Island Press.

Tiessen, H., Moir, J.O.. "Characterization of Available P by Sequential Extraction". In: Carter, M.R., and E.G. Gregorich. 2008. *Soil Sampling and Methods of Analysis*. 2nd ed. Canadian Society of Soil Science. CRC Press. Chapter 25. pp 293-306

United Nations, Department of Economic and Social Affairs. 2014. *World Urbanization Prospects - 2014 Review [Highlights]*. New York: United Nations.

USEPA. 2003. *Protecting Water Quality from Urban Runoff*. United States Environment Protection Agency. Washington, DC. EPA 841-F-03-003.

UTAD Botanical Garden, University of Trás-os-Montes e Alto Douro Botanical Garden. 2015a. Brachypodium phoenicoides. Accessed [September 22]. Available from http://jb.utad.pt/especie/brachypodium_phoenicoides.

UTAD Botanical Garden, University of Trás-os-Montes e Alto Douro Botanical Garden. 2015b. Lavandula stoechas subsp. luisieri." Accessed [September 22]. Available fromhttp://jb.utad.pt/especie/lavandula_stoechas.

UTAD Botanical Garden, University of Trás-os-Montes e Alto Douro Botanical Garden. 2015c. Rosmarinus officinalis. Accessed [September 22]. Available from http://jb.utad.pt/especie/rosmarinus_officinalis.

VanWoert, Nicholaus D., D. Bradley Rowe, Jeffrey A. Andresen, Clayton L. Rugh, R. Thomas Fernandez, and Lan Xiao. 2005. "Green Roof Stormwater Retention." *Journal of Environmental Quality* 34 (3): 1036–44.

Voyde, Emily, Elizabeth Fassman, and Robyn Simcock. 2010. "Hydrology of an Extensive Living Roof under Sub-Tropical Climate Conditions in Auckland, New Zealand." *Journal of Hydrology* 394 (3): 384–95.

Whalley, J. 1978. "The Landscape of the Roof." *Landscape Design*, no. 122: 7–25.

Wolfgang, Ansel, and Appl Roland. 2011*. Green Roof Policies - an International Review of Current Practices and Future Trends.* International Green Roof Association (IGRA).

Yilmaz, D., M. Sabre, L. Lassabatère, M. Dal, and F. Rodriguez. 2015. "Storm Water Retention and Actual Evapotranspiration Performances of Experimental Green Roofs in French Oceanic Climate." *European Journal of Environmental and Civil Engineering*.

Ziadi, N., Sen Tran, T.. "Mehlich 3 - Extractable Elements". In: Carter, M.R., and E.G. Gregorich. 2008. *Soil Sampling and Methods of Analysis*. 2nd ed. Canadian Society of Soil Science. CRC Press. Chapter 7. pp 81-88

APPENDICES

APPENDIX 1

Selected green roof policies by city, state or country

Canada - Quebec	• Quebec's Energy Board approved a \$10.76/m^2 incentive for green roof implementation in 2003, as long as the roof meets certain design criteria (Mishra 2004 cited by Getter and Rowe 2006).
Canada – Vancouver	• Developed a pilot program for the Southeast False Creek neighborhood, that requires all buildings to have at least 50 per cent green roof coverage (Lawlor et al. 2006).
China – Beijing	• The city has set the goal of greening 30 % of high-rise buildings and 60 % of low rise buildings (< 12 storeys) by 2008 (Grant and others 2006 cited by Gedge and Newton 2008).
Germany – Bonn	• Reduction of the landowners monthly storm water fees by 0.75 Euro/m^2 (Herman 2003 cited by Getter and Rowe 2006).
Germany – Boblingen, Frankfurt, Karlsruhe, Kassel, Leonberg, Stuttgart	• Direct financial support to roof greening ranging from €5 - €50 / m^2, or between 25 – 100% of the installation cost (Grant et al. 2003).
Germany – Cologne, Manheim	• 50 % reduction of the storm water fee (Herman 2003 cited by Getter and Rowe 2006).
Germany – Darmstadt	• Refund of up to 5000 € of the cost of installing a new green roof (Herman 2003 cited by Getter and Rowe 2006).
Germany – Esslingen	• Refund of up to 50% of the cost of installing a new green roof (Herman 2003 cited by Getter and Rowe 2006).
Germany – Munich	• Regulations in urban land-use plans, grants for voluntary installation of green roofs and a reduction in storm water fees; • Obligation to landscape all suitable flat roofs with a surface area >100m^2 (Wolfgang and Roland 2011)
Germany – Munster	• 80 % reduction in storm water drainage charges if a green roof is installed (Grant and others 2006 cited by Gedge and Newton 2008)
Singapore	• The city has set the goal of 50 ha of new "Skyrise Greenery Areas" by 2030; • Green roofs are a measure of compensation for new building projects; • Gross Floor Incentive Scheme for roofs and municipal allotment gardens; • Financial subsidies for sustainable landscaping of existing buildings in districts with especially large green area needs (Wolfgang and Roland 2011).
Switzerland	• Federal law requires all federal agencies to apply the 'Swiss Landscape Concept' when commissioning or rehabilitating federal buildings and installations (facilities must be compatible with natural settings and landscape) (Grant et al. 2003); • Laws require that 25% of all new commercial developments are greened in an attempt to maintain microclimates (Grant et al. 2003).
USA – Washington – Seattle	• Landscape strategies applying to all new development in neighborhood business districts, comprising more than four dwellings, more than 370 m^2 or with more than 20 parking spaces. It is intended to increase the amount and quality of landscape in dense urban areas (Gedge and Newton 2008).

APPENDIX 2

Hydrological performance of green roofs in urban areas – literature review

Authors, Year	Rainfall – Runoff Results		Growing medium	Vegetation	Location / Climate	Observations
Hutchinson et al. 2003	Average retention 69%		101.6 – 127 mm 4-5 inch depth 20% digested fibber 10% compost 22% course perlite 28% sandy loam	Succulents, grasses and other herbaceous	Portland, Oregon, USA Mild climate, moderate winter rainfall, dry summer	
Liu and Minor 2005	Average retention 57%		100 mm depth composite semi-rigid polymeric drainage and filter mat; root-anchoring mat	Vegetated	Toronto, Canada	The test plot with thinner growing medium periodically saturated during wet weather while the plot with thicker medium consistently exhibited a reduction in volume.
	Runoff delay 20-40 min summer		75 mm depth expanded polystyrene drainage panels and a geotextile filter fabric			
	Peak reduction summer 25%-60% Peak reduction winter 10% - 30%					
VanWoert et al. 2005	Average retention 48.7% Cumulative retention 27.2%	Light rain (<2mm) - 84.6%	20 mm depth gravel	No vegetation		
		Medium rain (2-6mm) - 37.7%				
		Heavy rain (>6mm) - 26.3%				
	Average retention 82.8% Cumulative retention 60.6%	Light rain - 97.9%	40% heat expanded slate 40% grade sand 10% Michigan peat 5% dolomite 3.33% compost yard waste 1.67% composted poultry litter	*Sedum acre* *S. album* *S. kamtschaticum ellacombianum* *S. pulchellum* *S. reflexum* *S. spurium*	Michigan State University, USA	
		Medium rain - 85.7%				
		Heavy rain - 65%				

Authors, Year	Rainfall – Runoff Results		Growing medium	Vegetation	Location / Climate	Observations
VanWoert et al. 2005	Cumulative retention 50.4%	Light rain - 99.6%	Same as above	No vegetation	Michigan State University, USA	
		Medium rain - 85.7%				
		Heavy rain - 52.6%				
	Cumulative retention 69.8%	Light rain - 95.1%	2% slope 25 mm depth Substrate characteristics as above	No vegetation		
		Medium rain - 82.9%				
		Heavy rain - 64.7%				
	Average retention 87% Cumulative retention 70.7%	Light rain - 97.1%	2% slope 40 mm depth Substrate characteristics as above	No vegetation		
		Medium rain - 85.5%				
		Heavy rain - 65.1%				
	Average retention 83.8% Cumulative retention 65.9%	Light rain - 94.9%	6.5% slope 40 mm depth Substrate characteristics as above	No vegetation		
		Medium rain - 83.1%				
		Heavy rain - 59.5%				
	Cumulative retention 68.1%	Light rain - 95.8%	6.5% slope 60 mm depth Substrate characteristics as above	No vegetation		
		Medium rain 84.6%				
		Heavy rain 62.0%				
Hathaway et al. 2008	Average retention 64%		75 mm depth Drainage layer: Hydrodrain 300 55% Perma Till 30% sand 15% compost cow manure	*Delosperma nubigenum* *Sedum reflexum* *S. sexangulare* *S. album* *S. album f. murale* *S. spurium* "Fuldaglut"	Wayne Community College, Goldsboro, North Carolina, USA	
	Average peak attenuation 77%					
	Average retention 64%		100 mm depth 3% slope Drainage layer: Floradrain FD40; System Filter SF Same growing media as above		Neuseway Nature Center in Kinston, North Carolina, USA	
	Average peak attenuation 88%					

<table>
<tr><th>Authors, Year</th><th colspan="2">Rainfall – Runoff Results</th><th>Growing medium</th><th>Vegetation</th><th>Location / Climate</th><th>Observations</th></tr>
<tr><td rowspan="3">Berghage et al. 2009</td><td rowspan="2">Cumulative retention 52.6%</td><td>Summer aprox. 95%</td><td rowspan="2">90 – 100 mm depth
Expanded clay with some compost amendment</td><td rowspan="2">Sedum spurium
Sedum album</td><td rowspan="3">Centre for Greenroof Research at Penn State, Pensilvania, USA</td><td rowspan="3">Field study</td></tr>
<tr><td>Winter aprox. 20%</td></tr>
<tr><td colspan="2">Cumulative retention 14.1%</td><td>Asphalt</td><td>No vegetation</td></tr>
<tr><td>Fioretti et al. 2010</td><td colspan="2">Average retention 68 ± 37%
Average peak attenuation 89 ± 15%</td><td>Non woven protection layer;
15 cm lapillus drainage layer; growing medium with mixed soil lapillus, pumice, zeolite and peat</td><td></td><td>University of Genova, North-West of Italy (Mediterranean climate)</td><td></td></tr>
<tr><td rowspan="5">Lundholm et al. 2010</td><td rowspan="5">Water capture on a 10 mm rain</td><td>0.90 kg</td><td rowspan="5">Non-woven water retention layer
Enkamat drainage/filter layer
Crushed brick, blond peat, perlite, sand and vegetable compost
Depth 60 mm</td><td>Grasses</td><td rowspan="5">Saint Mary's University Campus, Halifax, Nova Scotia, Canada (cold, humid, maritime climate)</td><td rowspan="5">Simulated rain</td></tr>
<tr><td>0.85 kg</td><td>Creeping shrubs, creeping forbs, tall forbs</td></tr>
<tr><td>0.83 kg</td><td>Sagina procumbens</td></tr>
<tr><td>0.68 kg</td><td>Deschampsia flexuosa</td></tr>
<tr><td>0.76 kg</td><td>Succulents</td></tr>
<tr><td rowspan="2">Palla et al. 2010</td><td colspan="2">Retention 33-48%</td><td>120 mm depth
lapillus, crushed brickwork, pumice, sand of brickwork and a blend of peat and vegetable compost</td><td rowspan="2"></td><td rowspan="2">University of Genova, North-West of Italy (Mediterranean climate)</td><td rowspan="2">Laboratory test bed; Designed simulated rainfall
Full scale experimental site</td></tr>
<tr><td colspan="2">Average retention 51.5%
Average peak attenuation 83.3%
Average runoff delay 5.17 hours</td><td>Non woven protection layer;
200 mm lapillus drainage layer; 200 mm growing medium with mixed soil lapillus, pumice, zeolite and peat</td></tr>
<tr><td>Stovin 2010</td><td colspan="2">Average retention 34%
Average peak attenuation 57%</td><td>Depth 80 m mixture of crushed brick and fines
Slope 1.5%
Filter membrane
Floradrain FD25 drainage layer</td><td>Sedum</td><td>University of Sheffield, UK (maritime climate)</td><td></td></tr>
</table>

Authors, Year	Rainfall – Runoff Results	Growing medium		Vegetation	Location / Climate	Observations
Voyde et al. 2010	Cumulative retention: 66% Average retention: 78% Average peak attenuation: 91%	80% pumice 20% composted bark fines Slope 1.2% Delta NP drainage mat	Depth 50 mm	*Acaena microphylla* ‘purpurea’ *Coprosma acerosa* ‘Hawera’ *Cotula australis* *Crassula sieberiana* *C.colligata* *Disphyma australe* *Festuca coxii* *Libertia peregrinans* *Mazus pumilo* *Pyrrosia eleagnifolia* *Selliera radicans* *Sedum* sp.	University of Auckland, New Zealand (subtropical humid climate with warm humid summers and mild winters)	
			Depth 70 mm			
		50% pumice 30% zeolite 20% composted bark fines Slope 1.2% Delta NP drainage mat	Depth 50 mm			Higher maximum water capacity
			Depth 70 mm			
		40% pumice 40% expanded clay 20% composted bark fines Slope 1.2% Delta NP drainage mat	Depth 50 mm	*Sedum rubrotinctum* *S. rupestre* *S. mexcicanum* *S. spurium* *S. abum* Mat with substrate and coconut coir		Higher saturated hydraulic conductivity Plot with 50 mm substrate depth and *Sedum* mat had the highest retention results due to the thick coconut coir fabric in the *Sedum* mat
			Depth 70 mm	*A. microphylla* ‘purpurea’ *C. acerosa* ‘Hawera’ *C. australis* *C. sieberiana* *C.colligata* *D. australe* *F. coxii* *L. peregrinans* *M. pumilo* *P. eleagnifolia* *S. radicans* *Sedum* sp.		
Stovin et al. 2011	Cumulative retention: 50.2% Average retention: 61% Average retention (storm with more than 1 year return period): 43% Average peak attenuation (storm with more than 1 year return period) :60%	Depth 80 mm Slope 1.5º Mixture of crushed brick and fines Filter membrane Floradrain® FD25 drainage layer		*Sedum* sp	Sheffield, UK (temperate climate)	

Authors, Year	Rainfall – Runoff Results	Growing medium		Vegetation	Location / Climate	Observations
Beecham et al. 2012	Average retention: 69%	Crushed brick, scoria, coir fibre and composted organics	Depth 100 mm	Unvegetated	University of South Australia, Adelaide, Australia	
			Depth 300 mm			
		Scoria-composted pine bark and hydrocell-flakes	Depth 100 mm			
			Depth 300 mm			
Fassman-Beck et al. 2013	Cumulative retention 66% Median retention (event) 75% Median peak attenuation (event) 89%	Pumice 40-80% Composted pine bark fines 20% and zeolite or expanded clay Slope 1.2% Depth 50-70 mm		*Sedum* sp.	University of Auckland, Auckland, Australia (subtropical climate)	
	Cumulative retention 48% Median retention (event) 55% Median peak attenuation (event) 73%	Pumice 70% Natural zeolite 10% Organic matter substrate blend 20%	Depth 100 mm	20 native species 18 non-native species	Landcare Research Office, East Tamaki, Auckland, Australia	
	Cumulative retention 57% Median retention (event) 66% Median peak attenuation (event) 74%		Depth 150 mm			
	Cumulative retention 66% Median retention (event) 72% Median peak attenuation (event) 86%	Pumice 60% Expanded clay 20% Compost based garden mix 20% Depth aprox. 100 mm		Native plants	Waitakere Civic Center, Auckland, Australia	
Harper et al. 2014	Average retention 60%	Arkalyte mix		17 *Sedum Phedimus takesimensis*	Missouri, USA	Retention results higher for GAF than Arkalyte mix in aprox 20% Retention of over 60% for storms below 5 cm
	Average retention 40%			Unvegetated		
	Average retention 60%	GAF’s Gardenscapes ™ green roof media		17 *Sedum Phedimus takesimensis*		

Authors, Year	Rainfall – Runoff Results	Growing medium	Vegetation	Location / Climate	Observations
Razzaghmanesh and Beecham 2014	Average retention 88.62% Peak attenuation 16.64%-95.83% Average runoff delay 17h	Intensive Crushed brick, scoria, coir fibre and composted organics Depth 300 mm	Four native plants	Adelaide, Australia (hot Mediterranean climate)	Highest retention
		Intensive Scoria, composted pine bark and hydrocell ® flakes Depth 300 mm			
	Average retention 74.02% Peak attenuation 16.64%-95.83% Average runoff delay 3h	Extensive Crushed brick, scoria, coir fibre and composted organics Depth 100 mm			
		Extensive Scoria, composted pine bark and hydrocell ® flakes Depth 100 mm			Lowest retention
Lee et al. 2015	Retention 13.8-34.4%	Volcanic materials and soil with peat, moss and perlite; Drainage plate — Depth 150 mm	*Sedum* sp.	Seoul National University Building, Gwanak-Gu, Seoul, Korea	
	Retention 42.8-60.8%	Depth 200 mm			
Mobilia et al. 2015	Overall retention Duration 10 min: aprox. 100% Duration 6h: 97.9 – 73.3% Duration 3 days: 82.6 – 41.1% Low intensity rainfall retention Duration 10 min: 98.5% Duration 6h: 91.4 – 97.9% Duration 3 days: 49.8 – 80.9%			Campus of the University of Salermo, Italy (Mediterranean climate)	Simulated rainfall and runoff events
Nawaz et al. 2015	Retention values ranged from 3.6% to 100% and the mean value was 66%. Average peak delay 224 min Average runoff delay 95 min	Depth 30 mm Slope<2% 20 mm drainage mat Substrate with *Sedum* mat	*Sedum acre* “aureum”, Sedum reflexum “blue spruce”, *Sedum album* “coral carpet”	University of Leeds, UK (maritime climate)	
Yilmaz et al. 2015	Retention 67.9 %	80 mm	No vegetation	Nantes, western France (oceanic climate)	For heavy rain events 120 mm retained more than 80 mm regardless of the vegetation.
	Retention 72.8 %	80 mm	*Sedum album*		
	Retention 78.0 %	120 mm	No vegetation		
	Retention 83.1 %	120 mm	*Sedum album*		
	Retention 83.4 %	120 mm	*Festuca glauca*		
	Retention 87.1 %	80 mm	*Dianthus deltoides*		

APPENDIX 3

Technical information

Ficha técnica — Referência 2045

Manta de protecção e retenção — SSM 45

Manta de retenção de água e nutrientes em fibra sintética utilizada como camada de protecção debaixo de coberturas extensivas, com enchimento em gravilha, pavimentos de cerâmica.

Reciclar para melhorar o meio ambiente

ETA-13/0668

Dados técnicos

Manta de protecção e retenção SSM 45

Manta de fibra de poliéster/polipropileno de grande qualidade, reciclado.

Espessura:	aprox. 5 mm
Peso:	aprox. 470 g/m²
Cor:	castanho
Capacidade de retenção de água:	aprox. 5 l/m²
Capacidade protectora testada segunda a EN ISO 13428:	⩾25%

Teste de resistência à tracção segundo Norma Alemã DIN 53857:

Tracção longitudinal:	> 8,5 kN/m
Dilatação longitudinal:	> 90 %

Teste CBR segundo normativa alemã DIN 54307:

Resistência à perfuração:	> 2400 N
Resistência classe:	3

Dimensão do rolo:

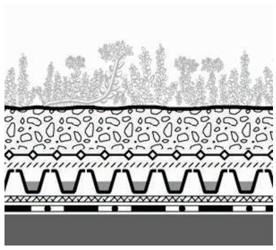
Largura	aprox. 2,00 m
Comprimento	aprox. 50,00 m

Características

- Resistência à força mecânica
- Capacidade de protecção testada segundo a normativa europea EN ISO 13428
- Retenção de água e nutrientes
- Resistente à decomposição
- Biológica e quimicamente neutra
- Compatível com materiais betuminosos e poliestireno
- Fabricado de fibras recicladas
- Instalação rápida e fácil

Exemplo de aplicação

Cobertura Extensiva



Nível de vegetação
“Zinco Sedum Mix ” ou “Sedum Floral”
Substrato
Sistema anti-queda Fallnet
Filtro sistema SF
Floradrain® FD 25-E
Manta de protecção e retenção SSM 45
Laje de cobertura com impermeabilização anti-raízes

Descrição para a memória técnica

Manta de fibras de alta qualidade, resistente à decomposição, com capacidade de protecção testada segundo a normativa europeia EN ISO 13428, resistência classe 3, espessura 5mm, peso 470 g/m², fornecimento e instalação como camada de protecção contra danos sobre a impermeabilização segundo as instruções do fabricante.

Produto: ZinCo Manta de protecção e retenção SSM 45

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Actualização 07/13; Autorização por ZinCo GmbH

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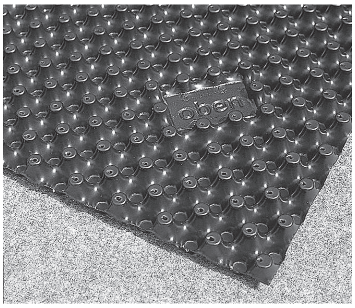
Ficha técnica — Referência 3028

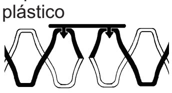
Floradrain® — FD 25-E



Elemento de drenagem e retenção de água de polietileno reciclado, resistente à pressão, para instalação em coberturas ajardinadas de tipo extensivo.

Reciclar para melhorar o meio ambiente

Clips de união de plástico



CE ETA-13/0668

Dados técnicos

Floradrain® FD 25-E

Elemento de drenagem e retenção de água fabricado em polietileno reciclado.

Material:	**HDPE (polietileno de alta densisade)**
Cor:	**Cinzento escuro**
Altura:	**aprox. 25 mm**
Peso:	**aprox. 1,7 kg/m²**
Diâmetro das aberturas de difusão:	**aprox. 2 mm**
Capacidade de retenção de água:	**aprox. 3 l/m²**
Volume de enchimento:	**aprox. 10 l/m²**
Resistência à compressão (vazío):	**> 270 kN/m²**
Capacidade de drenagem em superfície	**(EN ISO 12958):**
com 1 % de pendente:	**aprox. 0,59 l/(s·m)**
com 2 % de pendente:	**aprox. 0,85 l/(s·m)**
com 3 % de pendente:	**aprox. 1,05 l/(s·m)**
Dimensões:	**aprox. 1,00 m x 2,00 m**

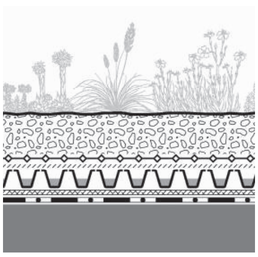
Acessórios: Clips de união de plástico Ref. 9620
(Conectam-se, com pressão, nas perfurações de difusão)

Características

- **Drenagem testada e com resultados conhecidos**
- **Supera as condições da Normativa Alemã DIN 4095**
- **Comprovado e testado a longo prazo**
- **Retenção de água, inclusive em coberturas com pendente**
- **Transitável**
- **Ligeiro e com pouca altura**
- **Biologicamente neutro**
- **Fácil e rápido de instalar**
- **"Clips" de união disponíveis como acessórios**

Exemplo de aplicação

Cobertura Extensiva



Nível de vegetação "Zinco Sedum Mix "

Sustrato"Sedum"

Sistema anti-queda "Fallnet"

Filtro SF

Floradrain® FD 25-E

Manta de protecção e retenção SSM 45

Laje de cobertura com impermeabilização anti-raízes

Descrição para a memória técnica

Elemento de drenagem e de retenção de água em polietileno; altura 25mm; suporta pressões superiores a 270 kN/m² , possui cavidades para retenção de água e aberturas de arejamento e difusão, alem de um sitema de canais multidireccionais na face inferior; capacidade de drenagem conforme a normativa EN ISO 12958; fornecimento e instalação de acordo com as instruções do fabricante.

Produto: ZinCo Floradrain ® FD 25-E

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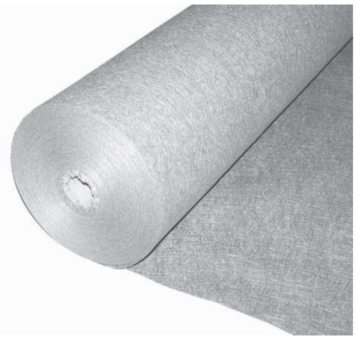
Ficha técnica

Referência 2100 - 2102

Filtro Sistema SF



Filtro de polipropileno termosoldado, utilizável como manta filtrante sobre elementos de drenagem para uma tensão e alongamento normal. Sem protecção anti-UV.

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Dados técnicos

Filtro sistema SF

Filtro de polipropileno termosoldado, sem protecção UV.

Espessura:	**0,60 mm aprox.**
Peso:	**100 g/m² aprox.**
Resistência à perfuração CBR segundo normativa EN ISO 12236:	**1100 N aprox.**
Resistência Classe:	**2**
Resistência à tracção (200 mm) segundo EN ISO 10319:	**7,0 kN/m aprox.**
Dilatação de ruptura:	**40 / 55 % aprox.**
Permeabilidade (H_{50}) segundo normativa EN ISO 11058:	**70 l/(m².s) aprox. (≙0.07 m/s)**
Abertura de poro (O_{90}) segundo normativa EN ISO 12956:	**95 µm aprox.**

Dimensões:

Comp.	**100,00 m**	**Larg.**	**2,00 m**	**Ref. 2100**
		Larg.	**1,00 m**	**Ref. 2102**
Comp.	**10,00 m**	**Larg.**	**2,00 m**	**Ref. 2101**

Características

- Cargabilidade mecânica
- Várias possibilidades de aplicação
- Resistente a todo tipo de ácidos e alcalinos naturais
- Química e biologicamente neutro
- Alta permeabilidade
- Rápido e fácil de instalar
- Resistente à decomposição

Exemplo de aplicação

"Cultivo Extensivo"

Descrição para a memória técnica

Filtro agulhado de polipropileno termosoldado por ambos lados, peso aprox. 100 g/m², resistência ao funcionamento CBR segundo a normativa EN ISO 12236: aprox. 1100 N, resistência classe 2, permeabilidade (H_{50}) segundo normativa EN ISO 11058: aprox. 70 l/(m².s) abertura de poro (O_{90}) segundo normativa EN ISO 12956: aprox. 95 m, fornecimento e colocação segundo instruções do fabricante.

Produto: ZinCo Filtro Sistema SF

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Substrato Landlab Intensivas
Substrato técnico para coberturas intensivas e semi-intensivas

1. NATUREZA E QUALIDADE DO SUBSTRATO

O substraSubstrato técnico Intensivas, Landlab – desenvolvido segundo a normativa FLL; constituído por componentes especiais com base mineral, que lhe conferem uma textura meia-grossa, capilaridade e drenagem elevadas e equilibradas. Este substrato caracteriza-se por apresentar uma elevada componente mineral, isento de parasitas, espécies infestantes e germes fito patogénicos e grande resistência estrutural.

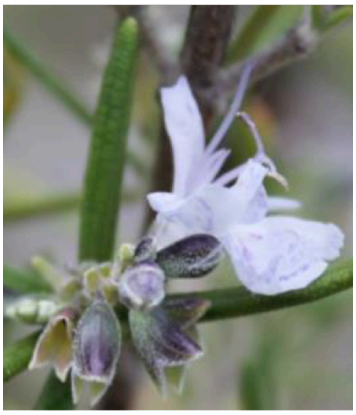
2. COMPOSIÇÃO DO SUBSTRATO TÉCNICO LANDLAB SEDUM

- Húmus de casca de pinho fermentado e certificado, granulometria 0-15mm
- Turfa loura seleccionada, granulometria 0-40 mm
- Argila Expandida - granulometria 2/4mm
- Rocha vulcânica especial, granulometria 3-9mm
- pH corrigido para 5.5-6.5
- Densidade específica: 750-500kg/m^3 humidade natural (50-60%)
- Densidade quando saturado: 650-700 kg/m^3

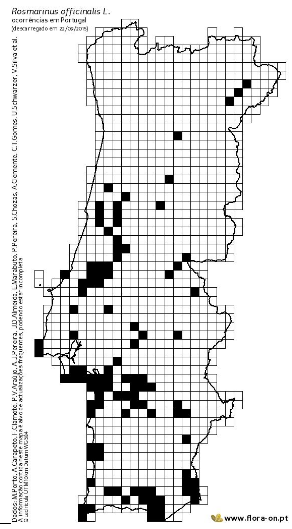
APPENDIX 4

Characteristics of the selected native plants

***Rosmarinus officinalis* L.**

Common name	English: Rosemary; Portuguese: Alecrim
Family	*Lamiaceae*
Order	*Lamiales*
Class	Magnoliopsida
Physiognomical type	Nanophanerophyte
Size	Up to 2 m x 2 m
Leaves	Evergreen; narrow, aromatic leaves
Flowers	2-lipped pale blue flowers borne in small clusters in the leaf axils; flowering from January to May
Habitat / Ecology	May be found in shrubberies, uncultivated lands; rupicolous, acid or basic soils, sandy, schist or calcareous soils

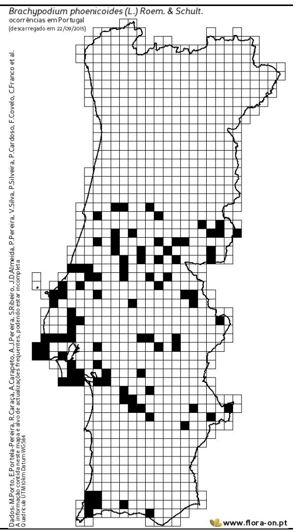


Curiosities	Good for honey production; aromatic

References: (Flora-on 2015c) (UTAD Botanical Garden 2015c) (RHS 2015) (Porto, Carapeto, et al. 2015)

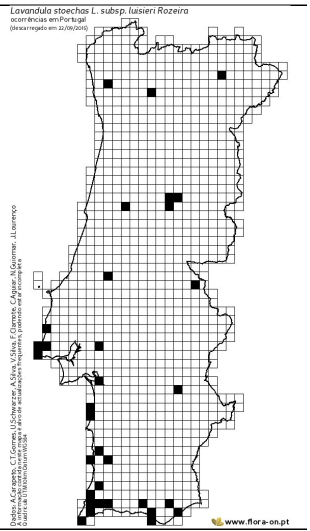
Brachypodium phoenicoides (L.) Roem. & Schult.

Common name	English: False brome; Portuguese: Braquipódio
Family	*Poaceae*
Order	*Poales*
Class	Magnoliopsida
Physiognomical type	Hemicryptophyte
Size	0.4 m
Leaves	Evergreen linear leaves
Flowers	Spikes flowering from May to August
Habitat / Ecology	May be found in shrubberies or uncultivated lands 
Curiosities	
References: (Flora-on 2015a) (UTAD Botanical Garden 2015a) (Porto, Portela-Pereira, et al. 2015)	

Lavandula stoechas subsp. _luisieri_ L.

Common name	English: French lavender; Portuguese: Rosmaninho
Family	*Lamiaceae*
Order	*Lamiales*
Class	Magnoliopsida
Physiognomical type	Nanophanerophyte
Size	0.6 m
Leaves	Evergreen; green-greyish leaves
Flowers	Purple spikes; flowering from March to June
Habitat / Ecology	May be found in shrubberies or uncultivated lands 
Curiosities	Aromatic

References: (Flora-on 2015b) (UTAD Botanical Garden 2015b) (Carapeto et al. 2015) (Marques 2008)

APPENDIX 5

Calibration of the tipping bucket rain gauges

Tipping bucket nº1

YEAR	DAY	HOUR	Depth (mm)	Nº of tips	Radius(m)	Area (m^2)	Total poored (mm)	Calibration factor
2014	192	1246	0,8	4	0,11	0,0385	12,98	1,32
2014	192	1246	0,8	4				
2014	192	1246	1	5				
2014	192	1246	0,8	4				
2014	192	1246	1	5				
2014	192	1246	0,8	4				
2014	192	1246	0,8	4				
2014	192	1246	0,8	4				
2014	192	1246	0,6	3				
2014	192	1246	0,8	4				
2014	192	1246	0,8	4				
2014	192	1246	0,6	3				
2014	192	1247	0,2	1				
					49	9,8	0,5	
small bucket capacity (mm)	0,2				Total tips	Total depth (mm)	Total poored (L)	

Tipping bucket nº2

YEAR	DAY	HOUR	Depth (mm)	Nº of tips	Radius(m)	Area (m^2)	Total poored (mm)	Calibration factor
2014	192	1633	0,4	2	0,11	0,04	12,98	1,04
2014	192	1633	0,6	3				
2014	192	1633	0,4	2				
2014	192	1633	0,4	2				
2014	192	1633	0,2	1				
2014	192	1633	0,2	1				
2014	192	1633	0,2	1				
2014	192	1634	0,2	1				
2014	192	1634	0,2	1				
2014	192	1634	0,2	1				
2014	192	1634	0,2	1				
2014	192	1634	0,2	1				
2014	192	1634	0	0				
2014	192	1634	0,2	1				
2014	192	1634	0,2	1				
2014	192	1634	0,2	1				
2014	192	1634	0,2	1				
2014	192	1634	0,2	1				
2014	192	1634	0,2	1				
2014	192	1635	0,2	1				
2014	192	1635	0,2	1				
					25	12,5	0,5	
small bucket capacity (mm)	0,2				Total tips	Total depth (mm)	Total poored (L)	

Tipping bucket nº3

YEAR	DAY	HOUR	Depth (mm)	Nº of tips	Radius(m)	Area (m^2)	Total poored (mm)	Calibration factor
2014	192	1709	1	2	0,11	0,04	12,98	1,18
2014	192	1709	1	2				
2014	192	1709	0,5	1				
2014	192	1709	1	2				
2014	192	1709	1	2				
2014	192	1709	1	2				
2014	192	1709	0,5	1				
2014	192	1709	1	2				
2014	192	1709	1	2				
2014	192	1709	0,5	1				
2014	192	1710	1	2				
2014	192	1710	0,5	1				
2014	192	1710	0,5	1				
2014	192	1710	0,5	1				
					22	11	0,5	
small bucket capacity (mm)	0,5				Total tips	Total depth (mm)	Total poored (L)	

Tipping bucket nº4

YEAR	DAY	HOUR	Depth (mm)	Nº of tips	Radius(m)	Area (m^2)	Total poored (mm)	Calibration factor
2014	192	1650	1	2	0,11	0,04	12,98	1,18
2014	192	1650	1	2				
2014	192	1650	1	2				
2014	192	1650	1	2				
2014	192	1650	1	2				
2014	192	1650	1	2				
2014	192	1650	1	2				
2014	192	1650	0,5	1				
2014	192	1650	1	2				
2014	192	1651	1	2				
2014	192	1651	0,5	1				
2014	192	1651	1	2				
					22	11	0,5	
small bucket capacity (mm)	0,5				Total tips	Total depth (mm)	Total poored (L)	

Tipping bucket nº5

DATE	Nº of tips	Radius (m)	Area (m^2)	Total poored (mm)	Calibration factor
05/06/14 16:32	4	0,11	0,04	12,98	1,20
05/06/14 16:32	13				
05/06/14 16:32	13				
05/06/14 16:33	15				
05/06/14 16:33	9				

small bucket capacity (mm)		Total tips	Total dept (mm)	Total poored (L)
		54	10,8	0,5
small bucket capacity (mm)	0,2	Total tips	Total dept (mm)	Total poored (L)

Tipping bucket nº6

DATE	Nº of tips	Radius (m)	Area (m^2)	Total poored (mm)	Calibration factor
05/06/14 17:23	6	0,11	0,04	12,98	1,18
05/06/14 17:23	7				
05/06/14 17:23	6				
05/06/14 17:24	3				

		22	11	0,5
small bucket capacity (mm)	0,5	Total tips	Total depth (mm)	Total poored (L)

Tipping bucket nº7

YEAR	DAY	HOUR	Depth (mm)	Nº of tips	Radius(m)	Area (m^2)	Total poored (mm)	Calibration factor
2014	192	1701	0,5	1	0,11	0,04	12,98	1,30
2014	192	1701	0,5	1				
2014	192	1701	1	2				
2014	192	1701	1	2				
2014	192	1701	1	2				
2014	192	1701	1	2				
2014	192	1701	1	2				
2014	192	1701	1	2				
2014	192	1701	0,5	1				
2014	192	1702	1	2				
2014	192	1702	0,5	1				
2014	192	1702	1	2				
					20	10	0,5	
small bucket capacity (mm) 0,5					Total tips	Total depth (mm)	Total poored (L)	

Tipping bucket nº8

DATE	Nº of tips	Radius (m)	Area (m^2)	Total poored (mm)	Calibration factor
05/06/14 17:23	6	0,11	0,04	12,98	1,18
05/06/14 17:23	7				
05/06/14 17:23	6				
05/06/14 17:24	3				

		22	11	0,5
small bucket capacity (mm)	0,5	Total tips	Total depth (mm)	Total poored (L)

Tipping bucket nº9

DATE	Depth (mm)	Nº of tips	Radius (m)	Area (m^2)	Total poored (mm)	Calibration factor
11/07/14 12:23	0,5	1	0,11	0,04	12,98	1,18
11/07/14 12:23	0,5	1				
11/07/14 12:23	1	2				
11/07/14 12:23	1	2				
11/07/14 12:23	1	2				
11/07/14 12:24	1	2				
11/07/14 12:24	0,5	1				
11/07/14 12:24	1	2				
11/07/14 12:24	1	2				
11/07/14 12:24	1	2				
11/07/14 12:24	1	2				
11/07/14 12:24	0,5	1				
11/07/14 12:24	0,5	1				
11/07/14 12:24	0,5	1				
			22	11	0,5	
small bucket capacity (mm) 0,5			Total tips	Total depth (mm)	Total poored (L)	

Tipping bucket nº10

YEAR	DAY	HOUR	Depth (mm)	Nº of tips	Radius(m)	Area (m^2)	Total poored (mm)	Calibration factor
2014	192	1235	0,6	3	0,11	0,04	12,98	1,20
2014	192	1235	0,8	4				
2014	192	1235	1	5				
2014	192	1235	1	5				
2014	192	1235	0,8	4				
2014	192	1235	1	5				
2014	192	1235	0,8	4				
2014	192	1235	1	5				
2014	192	1235	0,8	4				
2014	192	1235	0,8	4				
2014	192	1235	0,6	3				
2014	192	1235	0,8	4				
2014	192	1236	0,6	3				
2014	192	1236	0,2	1				
					54	10,8	0,5	
small bucket capacity (mm) 0,2					Total tips	Total depth (mm)	Total poored (L)	

Tipping bucket nº 11								
YEAR	DAY	HOUR	Depth (mm)	Nº of tips	Radius(m)	Area (m^2)	Total poored (mm)	Calibration factor
2014	192	1300	1	5	0,11	0,04	12,98	1,22
2014	192	1300	0,8	4				
2014	192	1301	1	5				
2014	192	1301	1	5				
2014	192	1301	0,8	4				
2014	192	1301	0,8	4				
2014	192	1301	1	5				
2014	192	1301	0,8	4				
2014	192	1301	0,8	4				
2014	192	1301	0,8	4				
2014	192	1301	0,8	4				
2014	192	1301	0,6	3				
2014	192	1301	0,4	2				
					53	10,6	0,5	
small bucket capacity (mm) 0,2					Total tips	Total depth (mm)	Total poored (L)	

Tipping bucket nº12								
YEAR	DAY	HOUR	Depth (mm)	Nº of tips	Radius(m)	Area (m^2)	Total poored (mm)	Calibration factor
2014	192	1552	0,6	3	0,11	0,04	12,98	1,20
2014	192	1552	0,8	4				
2014	192	1552	1	5				
2014	192	1552	1	5				
2014	192	1552	0,8	4				
2014	192	1552	1	5				
2014	192	1552	0,8	4				
2014	192	1552	1	5				
2014	192	1553	0,8	4				
2014	192	1553	0,8	4				
2014	192	1553	0,8	4				
2014	192	1553	0,6	3				
2014	192	1553	0,6	3				
2014	192	1553	0,2	1				
					54	10,8	0,5	
small bucket capacity (mm) 0,2					Total tips	Total depth (mm)	Total poored (L)	

Appendix 6

Substrate analysis by the INIAV laboratory

Instituto Nacional de Investigação Agrária e Veterinária, I.P.

Assunto: Envio de resultados analíticos referentes a 3 substratos ou suporte de culturas referentes ao Orçamento 2-2014 da UEISSAFSV – Laboratório de Solos de Oeiras

Oeiras, 24 de Julho de 2014

Quadro 1. Humidade e análise granulométrica de 3 substratos

Amostra nº	*Ref*	*>2 mm*	*>2 mm*	*2-0.2 mm*	*0.2-0.002 mm*	*<0.002 mm*	*Classificação Textural**
57198	S1	69.7	69.7	80.6	3.2	9.4	**
57199	S2	22.7	22.7	88.8	5.6	3.5	Arenosa
57200	S3	39.7	39.7	81.0	13.5	4.2	Arenosa

* Segundo Gomes & Silva (1962)
** Este substrato não se classificou por ser material essencialmente orgânico

Quadro 3. Caracterização química de 3 substratos

Amostra nº	*pH* em água*	*Humidade** (%) a 105ºC*	*MO*** (%)*	*Azoto Kjeldahl* (g kg^{-1})*	*Égner K_2O* (mg kg-^{1})*	*Riehm P_2O_5* (mg kg-^{1})*
57198	5.15	15.10	73.15	6.22	600	184
57199	7.38	2.30	7.40	0.99	218	126
57200	5.14	5.61	19.85	1.59	720	260

* A determinação destes parâmetros deveria ter sido efetuada com metodologia adequada para análise de substratos (EN 13652), mas a quantidade de amostra fornecida era insuficiente. Assim, optou-se por tratar a amostra como se fosse um solo.
** Humidade do material (<2 mm) após seco ao ar, em relação ao peso seco na estufa a 105ºC
** Para a determinação da matéria orgânica (MO) utilizou-se o método da via seca a 480ºC.

Quadro 4. Características físicas (valores médios observados) dos 3 substratos

	S1 Teor de água cm^3 cm^{-3}	*S2 Teor de água cm^3 cm^{-3}*	*S3 Teor de água cm^3 cm^{-3}*
Mva* (g cm^{-3})	0.383	0.883	0.531
pF 0.4	0.7728	0.5657	0.6405
pF 1.0	0.6727	0.4955	0.5309
pF 1.5	0.4521	0.2694	0.3526
pF 1.8	0.3692	0.2323	0.3069
pF 2.0	0.3319	0.2170	0.2863
pF 4.2	0.1535	0.1199	0.1360
Ksat (cm/dia)	5214	3675	7507

*Mva=Massa volúmica aparente

Maria da Conceição Gonçalves

mod.01.30 / 2 (2013)
GOVERNO DE PORTUGAL | MINISTÉRIO DA AGRICULTURA E DO MAR
Instituto Nacional de Investigação Agrária e Veterinária, I.P.
Unidade Estratégica de Investigação e Serviços de Sistemas Agrários e Florestais e Sanidade Vegetal
Av. da República, Quinta do Marquês, 2780-159 Oeiras - Portugal
Tel: (+ 351) 21 446 37 60 / 21 446 37 61
E.mail: ueissafsv@iniav.pt

APPENDIX 7

Rainfall events

Event	**Start** (day)	**End** (day)	**D** (h)	**d** (mm)	**V** (L)	I_{RFa} (mm h^{-1})	I_{RF} (mm h^{-1})	TP_{RF} (h)	**ADWP** (h)
5	258,10	258,12	0,27	3,80	9,50	14,25	21,60	258,10	87,87
6	258,46	258,51	1,07	5,40	13,50	5,06	14,40	258,48	15,00
7	259,13	259,25	2,90	7,20	18,00	2,48	8,40	259,14	8,30
8	259,86	260,23	8,90	2,80	7,00	0,31	7,20	260,22	14,50
9	261,48	262,19	17,03	5,20	13,00	0,31	16,80	261,48	29,83
10	262,52	262,52	0,17	0,40	1,00	2,40	1,20	262,52	7,90
11	263,27	263,38	2,57	1,80	4,50	0,70	7,20	263,36	17,83
12	265,60	265,67	1,70	1,80	4,50	1,06	4,80	265,62	53,43
13	266,51	266,53	0,43	12,80	32,00	29,54	57,60	266,52	20,03
14	270,51	270,52	0,20	0,60	1,50	3,00	2,40	270,51	95,37
15	280,01	280,47	11,07	7,00	17,50	0,63	7,20	280,34	227,83
16	281,98	282,14	3,77	8,80	22,00	2,34	9,60	282,07	36,17
17	282,55	282,56	0,07	0,40	1,00	6,00	2,40	282,55	9,90
18	282,80	283,00	4,83	5,80	14,50	1,20	14,40	282,84	5,80
19	284,74	286,69	46,93	59,60	149,00	1,27	84,00	286,61	41,57
20	288,03	288,18	3,73	7,60	19,00	2,04	13,20	288,13	31,97
21	291,16	291,25	2,10	2,40	6,00	1,14	3,60	291,19	71,40
22	307,59	309,01	34,17	20,40	51,00	0,60	36,00	307,87	62,10
23	310,62	311,31	16,50	3,60	9,00	0,22	4,80	311,18	62,10
24	312,38	312,87	11,80	8,00	20,00	0,68	16,80	312,62	25,53
25	313,26	313,53	6,43	2,00	5,00	0,31	2,40	313,26	9,43
26	314,45	316,24	43,07	46,40	116,00	1,08	60,00	314,84	21,87
27	317,06	318,40	32,17	33,80	84,50	1,05	36,00	317,75	19,70
28	318,70	319,84	27,37	15,00	37,50	0,55	10,80	319,42	7,10
29	322,64	324,84	52,77	107,40	268,50	2,04	56,40	323,77	67,13
30	326,79	326,97	4,27	1,00	2,50	0,23	1,20	326,79	46,67
31	327,54	327,84	7,30	6,60	16,50	0,90	4,80	327,54	13,63
32	330,33	330,95	15,03	30,40	76,00	2,02	30,00	330,63	59,60
33	331,74	332,26	12,53	32,60	81,50	2,60	55,20	331,90	18,83
34	338,25	338,30	1,30	0,60	1,50	0,46	2,40	338,25	18,83
35	347,16	347,90	17,73	33,80	84,50	1,91	14,40	347,69	212,50
36	350,31	350,43	2,70	0,60	1,50	0,22	1,20	350,31	57,90
37	379,02	379,18	3,87	0,60	1,50	0,16	2,40	379,02	312,33
38	380,31	380,32	0,20	0,60	1,50	3,00	2,40	380,31	27,07
39	380,61	381,71	26,40	18,20	45,50	0,69	12,00	380,67	7,20
40	382,72	383,86	27,40	49,00	122,50	1,79	40,80	383,07	24,10
41	385,13	385,71	13,73	8,40	21,00	0,61	6,00	385,15	30,57
42	386,52	387,45	22,30	2,80	7,00	0,13	2,40	386,57	19,50
43	388,08	388,62	13,03	1,20	3,00	0,09	1,20	388,08	8,07
44	394,97	397,73	66,43	16,20	40,50	0,24	9,60	396,68	152,13
45	398,57	398,81	5,77	1,60	4,00	0,28	4,80	398,57	20,07
46	399,51	399,74	5,40	1,20	3,00	0,22	3,60	399,73	16,73
47	402,66	402,77	2,67	1,20	3,00	0,45	2,40	402,72	70,07
48	406,41	406,84	10,33	3,60	9,00	0,35	2,40	406,76	87,33
49	409,83	409,85	0,53	0,40	1,00	0,75	1,20	409,83	71,67
50	410,61	410,89	6,87	4,00	10,00	0,58	1,20	410,77	18,03
51	417,08	417,20	2,93	1,20	3,00	0,41	1,20	417,08	148,30

D (h) - duration
d_{RF} (mm) - depth
V (L) - volume
I_{RFa} (mm h^{-1}) - maximum rainfall intensity in 10 minutes
I_{RF} (mm h^{-1}) - average rainfall intensity
TP_{RF} (h) - time of rainfall peak
ADWP (h) - antecedent dry weather period

APPENDIX 8
Rainfall - runoff relations

Test bed S2_Moss

Event	**RD** (h)	**R** (%)	**PA** (%)	**PD** (h)
5	INF	100,00	100,00	INF
6	INF	100,00	100,00	INF
7	1,10	68,96	90,91	2,77
8	NA	NA	NA	NA
9	INF	100,00	100,00	INF
10	INF	100,00	100,00	INF
11	INF	100,00	100,00	INF
12	INF	100,00	100,00	INF
13	NA	NA	NA	NA
14	INF	100,00	100,00	INF
15	NA	NA	NA	NA
16	INF	100,00	100,00	INF
17	INF	100,00	100,00	INF
18	2,37	82,61	98,86	1,70
19	6,87	38,87	77,35	0,07
20	0,33	38,07	82,24	0,67
21	INF	100,00	100,00	INF
22	NA	80,28	96,56	NA
23	3,43	75,02	96,15	0,43
24	0,70	56,80	86,80	0,97
25	0,03	34,55	93,07	3,53
26	0,07	41,11	75,82	0,10
27	0,17	30,08	59,81	0,17
28	0,07	28,79	81,35	0,43
29	0,73	40,98	73,56	0,20
30	0,07	58,73	92,30	1,10
31	0,13	32,61	84,99	7,07
32	1,47	33,21	52,75	0,37
33	0,00	37,85	73,59	0,17
34	35,17	99,49	99,23	35,17
35	0,80	47,36	30,57	0,13
36	1,93	89,73	98,46	1,93
37	INF	100,00	100,00	INF
38	INF	100,00	100,00	INF
39	1,40	73,19	88,30	1,70
40	0,17	42,83	68,11	0,13
41	0,47	47,35	80,60	1,13
42	0,03	39,28	95,38	1,20
43	0,07	30,19	92,30	0,43
44	5,33	48,10	90,76	0,00
45	0,17	48,03	81,52	0,33
46	0,00	51,49	98,46	0,00
47	INF	100,00	100,00	INF
48	INF	100,00	100,00	INF
49	INF	100,00	100,00	INF
50	8,87	95,46	98,46	5,00
51	INF	100,00	100,00	INF

Test bed S1_Mix of Plants and Moss

Event	**RD** (h)	**R** (%)	**PA** (%)	**PD** (h)
5	INF	100,00	100,00	INF
6	INF	100,00	100,00	INF
7	3,50	95,02	98,94	3,44
8	9,00	95,25	99,08	0,24
9	INF	100,00	100,00	INF
10	INF	100,00	100,00	INF
11	INF	100,00	100,00	INF
12	INF	100,00	100,00	INF
13	NA	NA	NA	NA
14	INF	100,00	100,00	INF
15	INF	100,00	100,00	INF
16	INF	100,00	100,00	INF
17	INF	100,00	100,00	INF
18	INF	100,00	100,00	INF
19	14,37	58,57	77,35	0,07
20	0,27	63,87	99,83	0,63
21	INF	100,00	100,00	INF
22	7,00	99,47	98,95	0,27
23	INF	100,00	100,00	INF
24	INF	100,00	100,00	INF
25	INF	100,00	100,00	INF
26	3,97	50,95	68,66	0,13
27	0,10	24,17	55,46	0,73
28	0,13	29,85	89,53	0,43
29	1,87	25,67	67,17	0,17
30	0,37	86,69	94,46	1,00
31	0,13	45,18	90,30	0,73
32	1,67	25,89	42,34	0,43
33	0,07	25,62	66,90	0,17
34	INF	100,00	100,00	INF
35	1,07	55,51	51,80	0,20
36	INF	100,00	100,00	INF
37	INF	100,00	100,00	INF
38	INF	100,00	100,00	INF
39	INF	100,00	100,00	INF
40	2,07	36,57	94,35	0,23
41	0,33	50,50	97,04	1,13
42	0,17	70,04	99,08	0,00
43	0,10	83,37	98,15	0,10
44	9,97	76,61	99,31	0,00
45	0,13	82,91	99,54	0,13
46	0,80	90,14	99,38	0,00
47	INF	100,00	100,00	INF
48	INF	100,00	100,00	INF
49	INF	100,00	100,00	INF
50	INF	100,00	100,00	INF
51	INF	100,00	100,00	INF

Test bed S1_*Rosmarinus officinalis*

Event	**RD** (h)	**R** (%)	**PA** (%)	**PD** (h)
5	INF	100,00	100,00	INF
6	INF	100,00	100,00	INF
7	2,80	87,51	98,05	2,84
8	0,34	81,83	97,73	0,27
9	INF	100,00	100,00	INF
10	INF	100,00	100,00	INF
11	INF	100,00	100,00	INF
12	INF	100,00	100,00	INF
13	NA	NA	NA	NA
14	INF	100,00	100,00	INF
15	INF	100,00	100,00	INF
16	INF	100,00	100,00	INF
17	INF	100,00	100,00	INF
18	INF	100,00	100,00	INF
19	13,40	52,71	80,72	0,07
20	0,00	38,79	85,13	0,63
21	INF	100,00	100,00	INF
22	6,80	92,83	87,13	0,17
23	INF	100,00	100,00	INF
24	12,53	99,66	99,68	6,73
25	0,30	90,46	97,73	0,30
26	1,17	44,27	74,38	0,10
27	0,10	25,30	61,08	0,70
28	0,07	20,53	90,41	0,00
29	0,77	29,24	71,97	0,17
30	0,13	51,84	90,91	0,27
31	0,10	31,03	89,78	0,73
32	0,47	24,53	51,48	0,43
33	0,10	21,01	71,56	0,17
34	INF	100,00	100,00	INF
35	1,00	51,34	44,35	0,17
36	2,40	92,43	95,46	2,40
37	INF	100,00	100,00	INF
38	INF	100,00	100,00	INF
39	3,57	99,80	99,55	2,07
40	0,93	24,03	67,00	0,17
41	0,17	40,29	90,91	1,23
42	0,17	38,99	97,73	8,37
43	0,07	40,94	90,91	0,07
44	10,60	67,36	96,02	0,00
45	0,17	55,14	97,73	0,17
46	0,17	66,68	98,49	INF
47	INF	100,00	100,00	INF
48	INF	100,00	100,00	INF
49	INF	100,00	100,00	INF
50	INF	100,00	100,00	INF
51	INF	100,00	100,00	INF

RD (h) - runoff delay **R** (%) - retention
PA (%) - peak attenuation **PD** (h) - peak delay

Test bed S1_*Brachypodium phoenicoides*

Event	**RD** (h)	**R** (%)	**PA** (%)	**PD** (h)
5	INF	100,00	100,00	INF
6	INF	100,00	100,00	INF
7	0,67	63,85	40,99	2,84
8	0,07	68,43	88,98	0,34
9	0,83	90,94	99,70	0,83
10	INF	100,00	100,00	INF
11	INF	100,00	100,00	INF
12	INF	100,00	100,00	INF
13	NA	NA	NA	NA
14	INF	100,00	100,00	INF
15	INF	100,00	100,00	INF
16	INF	100,00	100,00	INF
17	INF	100,00	100,00	INF
18	INF	100,00	100,00	INF
19	7,17	52,26	82,24	0,07
20	0,10	44,88	76,34	0,50
21	INF	100,00	100,00	INF
22	6,77	98,74	99,86	0,37
23	INF	100,00	100,00	INF
24	5,80	97,11	99,70	0,00
25	0,27	78,11	95,87	3,73
26	0,30	37,87	75,63	0,13
27	0,13	33,85	64,75	0,70
28	0,10	33,13	83,93	0,40
29	0,80	32,35	73,98	0,00
30	0,07	49,60	91,74	0,30
31	0,13	32,28	84,51	7,10
32	1,43	33,36	55,05	0,40
33	0,07	33,50	73,60	0,17
34	INF	100,00	100,00	INF
35	1,07	43,46	38,03	0,17
36	0,47	83,48	95,87	0,47
37	INF	100,00	100,00	INF
38	INF	100,00	100,00	INF
39	20,87	95,82	98,76	19,37
40	0,40	24,09	70,96	0,17
41	0,07	39,61	79,34	1,17
42	0,13	38,92	95,87	1,00
43	0,00	18,76	91,74	4,20
44	8,33	57,77	93,29	0,00
45	0,00	45,78	97,93	0,10
46	0,20	54,56	98,62	0,00
47	INF	100,00	100,00	INF
48	INF	100,00	100,00	INF
49	INF	100,00	100,00	INF
50	INF	100,00	100,00	INF
51	INF	100,00	100,00	INF

Test bed S1_*Rosmarinus officinalis*_2

Event	**RD** (h)	**R** (%)	**PA** (%)	**PD** (h)
5	INF	100,00	100,00	INF
6	INF	100,00	100,00	INF
7	0,40	64,32	90,76	2,67
8	0,07	63,04	95,38	0,07
9	7,43	98,58	99,67	7,43
10	INF	100,00	100,00	INF
11	INF	100,00	100,00	INF
12	INF	100,00	100,00	INF
13	NA	NA	NA	NA
14	INF	100,00	100,00	INF
15	INF	100,00	100,00	INF
16	INF	100,00	100,00	INF
17	INF	100,00	100,00	INF
18	5,23	95,54	99,62	4,27
19	5,97	34,16	73,93	0,07
20	0,07	25,23	78,16	0,63
21	INF	100,00	100,00	INF
22	7,20	99,50	99,38	0,47
23	INF	100,00	100,00	INF
24	7,93	95,15	99,34	2,47
25	0,13	75,98	95,38	0,13
26	0,23	26,94	64,43	0,10
27	0,10	15,42	50,72	0,13
28	0,07	13,33	89,73	0,00
29	0,77	17,07	61,47	0,17
30	0,20	45,48	86,14	0,50
31	0,10	21,04	86,14	0,67
32	1,43	20,49	42,90	0,27
33	0,00	16,58	62,14	0,17
34	INF	100,00	100,00	INF
35	1,80	45,79	36,09	0,17
36	2,57	93,84	95,38	2,57
37	INF	100,00	100,00	INF
38	INF	100,00	100,00	INF
39	INF	100,00	100,00	INF
40	1,70	20,55	62,09	0,13
41	0,17	35,76	86,14	1,13
42	0,03	30,37	93,07	1,03
43	0	33,78	90,76	0
44	10,33	62,64	95,96	0,00
45	0,13	49,76	96,54	0,13
46	0,30	61,50	96,92	INF
47	INF	100,00	100,00	INF
48	INF	100,00	100,00	INF
49	INF	100,00	100,00	INF
50	INF	100,00	100,00	INF
51	INF	100,00	100,00	INF

Test bed S1_*Brachypodium phoenicoides*_2

Event	**RD** (h)	**R** (%)	**PA** (%)	**PD** (h)
5	INF	100,00	100,00	INF
6	1,50	90,15	98,93	1,57
7	0,07	54,40	88,79	2,54
8	0,04	53,10	96,80	0,14
9	0,27	83,98	99,31	5,27
10	INF	100,00	100,00	INF
11	3,03	99,47	99,91	0,90
12	INF	100,00	100,00	INF
13	NA	NA	NA	NA
14	INF	100,00	100,00	INF
15	INF	100,00	100,00	INF
16	INF	100,00	100,00	INF
17	INF	100,00	100,00	INF
18	2,17	81,22	99,20	2,37
19	3,07	42,73	83,30	0,23
20	0,03	31,51	81,80	0,60
21	1,67	95,20	98,93	1,40
22	6,80	99,98	99,95	0,10
23	INF	100,00	100,00	INF
24	5,93	91,55	99,43	5,43
25	0,03	40,58	95,20	3,47
26	0,00	35,05	75,82	0,10
27	0,03	25,27	62,15	0,20
28	0,03	19,39	84,70	0,43
29	0,47	31,66	73,66	0,40
30	0,03	42,02	93,59	0,53
31	0,03	32,25	87,59	7,10
32	0,50	30,26	52,46	0,37
33	0,07	29,53	73,64	0,30
34	INF	100,00	100,00	INF
35	1,07	47,89	40,87	0,17
36	0,27	68,50	98,40	2,40
37	INF	100,00	100,00	INF
38	INF	100,00	100,00	INF
39	1,60	95,92	99,20	19,30
40	0,17	29,76	68,72	0,20
41	0,03	18,24	86,87	1,13
42	0,03	32,05	67,17	8,30
43	0,03	5,24	93,59	9,97
44	8,40	58,38	93,59	0,00
45	0,10	48,75	98,80	0,10
46	0,00	45,28	98,93	0,00
47	INF	100,00	100,00	INF
48	INF	100,00	100,00	INF
49	INF	100,00	100,00	INF
50	19,73	99,44	98,40	15,87
51	INF	100,00	100,00	INF

RD (h) - runoff delay **R** (%) - retention
PA (%) - peak attenuation **PD** (h) - peak delay

Test bed S2_*Lavandula luisieri*

Event	**RD** (h)	**R** (%)	**PA** (%)	**PD** (h)
5	INF	100,00	100,00	INF
6	1,34	91,76	96,97	1,40
7	0,17	61,13	94,81	2,90
8	0,00	60,41	97,73	0,20
9	0,73	90,91	99,68	0,73
10	INF	100,00	100,00	INF
11	INF	100,00	100,00	INF
12	INF	100,00	100,00	INF
13	NA	NA	NA	NA
14	INF	100,00	100,00	INF
15	INF	100,00	100,00	INF
16	INF	100,00	100,00	INF
17	INF	100,00	100,00	INF
18	2,07	70,86	98,11	1,23
19	5,03	33,01	80,34	0,07
20	0,07	27,91	89,68	0,60
21	1,67	97,73	98,49	1,40
22	6,83	99,87	99,85	0,10
23	INF	100,00	100,00	INF
24	7,47	92,50	99,35	2,17
25	0,40	74,56	95,46	4,70
26	0,13	26,37	72,47	0,10
27	0,07	17,98	58,36	0,70
28	0,17	19,80	92,93	0,00
29	1,07	21,14	70,71	0,13
30	0,10	63,66	90,91	1,10
31	0,27	32,13	93,19	7,17
32	1,73	23,19	50,75	0,40
33	0,07	17,22	70,37	0,17
34	INF	100,00	100,00	INF
35	NA	45,27	36,02	NA
36	3,07	95,46	95,46	3,07
37	INF	100,00	100,00	INF
38	INF	100,00	100,00	INF
39	2,90	95,61	99,09	21,90
40	0,33	46,30	66,60	0,20
41	0,37	42,67	91,82	1,20
42	0,10	39,32	95,46	0,37
43	0,23	37,16	95,46	0,00
44	10,03	66,52	97,16	0,00
45	0,07	77,29	98,86	0,07
46	0,50	69,71	98,49	0,00
47	INF	100,00	100,00	INF
48	INF	100,00	100,00	INF
49	INF	100,00	100,00	INF
50	5,20	99,77	95,46	1,33
51	INF	100,00	100,00	INF

Test bed S2_Bare soil

Event	**RD** (h)	**R** (%)	**PA** (%)	**PD** (h)
5	INF	100,00	100,00	INF
6	0,67	82,89	97,31	0,60
7	0,24	40,71	65,68	2,57
8	0,34	56,11	96,92	0,30
9	0,67	77,43	99,01	5,53
10	0,57	97,69	95,38	0,57
11	3,33	97,43	99,23	1,20
12	INF	100,00	100,00	INF
13	NA	NA	NA	NA
14	INF	100,00	100,00	INF
15	13,93	97,36	99,23	6,10
16	NA	NA	NA	NA
17	NA	NA	NA	NA
18	0,20	34,36	80,75	0,50
19	2,27	50,58	80,53	0,07
20	0,20	54,65	71,86	0,47
21	2,30	93,46	98,46	1,47
22	NA	85,37	98,92	NA
23	7,27	67,66	95,38	0,33
24	1,40	54,03	85,15	0,93
25	0,07	26,08	93,07	0,53
26	0,13	47,03	73,30	0,13
27	0,30	35,07	59,34	0,17
28	0,33	46,04	69,71	0,37
29	0,83	38,68	71,10	0,00
30	0,53	46,41	90,76	0,77
31	0,13	24,82	79,21	1,03
32	1,63	33,10	48,81	0,30
33	0,27	28,52	70,67	0,13
34	NA	NA	NA	NA
35	0,87	40,32	29,55	0,03
36	3,13	95,38	95,38	3,13
37	INF	100,00	100,00	INF
38	INF	100,00	100,00	INF
39	3,03	74,01	98,61	1,83
40	0,33	21,93	93,07	0,13
41	0,57	34,00	91,68	1,13
42	0,23	25,09	97,69	0,00
43	0,13	22,23	95,38	0,13
44	7,90	44,56	97,69	0,00
45	0,27	40,52	98,85	0,27
46	0,33	45,33	98,46	0,00
47	INF	100,00	100,00	INF
48	INF	100,00	100,00	INF
49	INF	100,00	100,00	INF
50	INF	100,00	100,00	INF
51	INF	100,00	100,00	INF

Test bed S2_Moss_2

Event	**RD** (h)	**R** (%)	**PA** (%)	**PD** (h)
5	INF	100,00	100,00	INF
6	INF	100,00	100,00	INF
7	2,47	83,47	90,91	2,70
8	NA	NA	NA	NA
9	INF	100,00	100,00	INF
10	INF	100,00	100,00	INF
11	INF	100,00	100,00	INF
12	INF	100,00	100,00	INF
13	NA	NA	NA	NA
14	INF	100,00	100,00	INF
15	NA	NA	NA	NA
16	INF	100,00	100,00	INF
17	INF	100,00	100,00	INF
18	1,40	69,30	93,56	0,77
19	3,77	43,64	81,76	0,13
20	0,33	39,51	68,61	0,50
21	2,87	92,43	98,49	2,20
22	NA	96,53	99,39	NA
23	7,60	73,75	96,59	2,87
24	1,17	76,49	92,86	1,03
25	0,00	62,29	95,46	0,80
26	0,03	46,66	76,01	0,13
27	0,60	33,55	61,69	0,17
28	0,37	40,03	76,28	0,40
29	0,93	27,68	71,00	0,13
30	0,43	64,56	90,91	0,63
31	0,13	34,20	82,96	7,07
32	1,63	26,74	50,03	0,37
33	0,03	23,72	71,06	0,13
34	NA	NA	NA	NA
35	0,97	58,28	36,02	0,07
36	4,13	98,49	95,46	4,13
37	INF	100,00	100,00	INF
38	INF	100,00	100,00	INF
39	3,97	83,82	95,46	18,23
40	0,00	26,77	68,47	0,13
41	0,67	41,27	67,29	1,17
42	0,33	35,10	18,23	8,40
43	0,03	33,37	90,91	0,20
44	8,87	52,78	91,48	0,00
45	0,07	41,51	97,73	0,07
46	0,17	49,27	98,49	0,00
47	INF	100,00	100,00	INF
48	3,93	98,38	98,18	0,00
49	0,47	98,18	98,18	0,47
50	0,43	98,00	96,37	0,00
51	0,57	97,88	98,18	0,57

RD (h) - runoff delay **R** (%) - retention
PA (%) - peak attenuation **PD** (h) - peak delay

APPENDIX 9

Events in which no runoff occurred

Rainfall Class	Events	Treatments					
		S1_PM	S1_R	S1_B	S2_L	S2_M	S2_BS
LS	10						
	12						
	14						
	17						
	21						
	34						
	36						
	38						
	47						
	49						
	51						
LM	25						
	30						
	31						
	37						
	43						
	45						
	46						
	48						
	50						
LL	23						
	42						
MS	6						
	7						
	11						
MM	8						
	15						
	16						
	18						
	20						
	24						
	41						
ML	9						
	28						
	35						
	39						
	44						
HS	5						
	13						
HM	33						
HL	19						
	22						
	26						
	27						
	29						
	32						
	40						

No runoff

Events eliminated due to technical problems